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ON A POSSIBLE REVERSAL OF DEEP-SEA CIRCULATION AND ITS INFLUENCE ON GEOLOGIC CLIMATES[1]

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The control of secular climates is obviously a condition prerequisite to biologic continuity. The preservation of a narrow range of temperature and a limited variation of atmospheric constituents throughout the millions of years of the biologic past was absolutely essential to organic evolution. Continued preservation for millions of years to come seems equally a condition precedent to an intellectual and spiritual evolution commensurate with the physical and biological evolutions that have preceded it. Only such a prolonged evolution of the intellectuality now just dawning gives full moral satisfaction to our conception of the sum-total of terrestrial history.

The narrowness of the range to which temperatures must be confined to permit progressive organic and intellectual evolution takes on its true meaning only when we recall that the natural temperature range on the earth's surface is sixteen times as great as this, while that affecting the solar family is at least sixty times as great. For a hundred million years, more or less, this narrow range of temperature has been maintained quite without break of continuity, unless geologists and biologists are altogether in error in their inductions. On the further maintenance of this continuity hang future interests of transcendent moment.

[1] Published by permission of the President of the Carnegie Institution, under whose auspices these studies have been prosecuted. Read, with unimportant alterations, before the American Philosophical Society at the Franklin Bicentennial Celebration.

So, too, the maintenance of a narrow range of atmospheric constitution, notably in the critical element carbon dioxide, has been equally indispensable. These two critical limitations of temperature and of constitution seem also to have been interdependently correlated with one another.

The climatic problem is as difficult as it is important. The factors are so many, so elusive, so imperfectly determined, perhaps even so imperfectly determinable, that the utmost patience and assiduity are a duty of the investigator, and the utmost charity of judgment an obligation of fellow-scientists. I am persuaded, however, that tentative analyses of the tangle of factors are an indispensable aid to the future solution of the problem. One of the gravest difficulties confronting us today is the imperfection of observations and the inconclusiveness of experimentation; and this arises in no small degree from the lack of such patient preliminary analyses of the problem as shall bring into sharp recognition the occult things that are to be observed and the precise experimental determinations which alone can really aid in the solution. If the little contribution of this paper shall have any value at all, it will lie in its suggestive relations to the larger problem of secular climates, past and prospective.

As this larger problem has recently assumed, with some of us, a phase much at variance with its more familiar aspects, it may need to be briefly sketched. It has been customary to assign to the primitive earth a climate quite beyond the Miltonian conception of Gehenna in its fiery intensity, and to predict an impending refrigeration scarcely inferior in antithetic severity. The familiar conception of the sum-total of atmospheric history as a decline from one excess to another as the sequence of thermal wastage, is a logical deduction from the hypothetical derivation of the earth from a gaseous or quasi-gaseous nebula through gravitative condensation. To some of us, however, such a derivation seems inconsistent with the dynamics of the present solar system, and an alternative hypothesis has been formulated to meet the supposed requirements of existing phenomena. The acceptance of this requires a reconstruction of the whole conception of geologic climates. The new view discards the primitive molten state as a necessary condition, and presents the alternative of a slow growth of the earth by planetesimal accessions. This

alternative involves a slow growth of the atmosphere also, until it reached a volume similar to the present, when its growth is assumed to have been arrested and thereafter limited by the interplay of opposing agencies. These agencies are thought to have held it ever since within so narrow a range of oscillation as to foster organic evolution. A continuance of the same control offers ground for hope of a perpetuation of conditions congenial to organic and intellectual life, through a period to which no definite limits can now be set beyond the presumption that there must ultimately be a limit. The inevitable cooling of a once white-hot earth plays no part in this prognosis. The agencies of atmospheric maintenance and control thus force themselves upon consideration as factors of supreme importance.

The assigned agencies of atmospheric *restraint* are molecular velocities, chemical combination, and condensation. By virtue of the first, the lighter constituents are reduced to a minimum and all constituents are restricted within certain large limits. By virtue of the second, the chemically active factors are kept down to states of dilution compatible with organic evolution, while the inert elements have probably been permitted to increase steadily. By the third, the excess of water-vapor has been condensed into the ocean, which has probably increased rather than diminished through the ages.

The postulated agencies of atmospheric *supply* are accessions from without and emanations from within, of which Vesuvius has just been giving us an impressive illustration.

To the interplay of these opposing agencies of loss and gain is assigned the maintenance of the requisite narrow range of atmospheric constitution, of temperature, and of associated conditions. Under this general resetting of fundamental conceptions, the question of climatic regulation takes on very concrete aspects and presents specific lines of study.

Subsidiary to these narrow limitations, recognition of pronounced variations is forced upon us by a growing mass of geologic evidence. Throughout most of the well-known geologic periods, the poleward distribution of life implies warm climates, even as high as 70° and 80° of latitude. How life of subtropical types could have survived the long polar nights is one of the most obdurate puzzles of the

earth's climatology. It becomes all the more strenuous if we cast aside all resort to an early fervid state and a molten interior. Quite irrespective of primitive conceptions, however, the edge of the problem has sharpened as we have been forced to recognize that *between* the warm polar stages there were episodes of glaciation in strangely low latitudes. It appears necessary now to accept as demonstrative the evidences of extensive glaciation in India, Australia, and South Africa in the midst of the later coal-forming stages of the Paleozoic era. The glacial beds lie even between coal beds of Permian or Permo-Carboniferous age; while, strangely enough, the areas of glaciation approach, and even overlap, the tropics of Cancer and Capricorn. And yet, figs and magnolias have grown in Greenland since, and mild polar climates are as well authenticated after as before this climacteric glaciation. Less complete evidences from China[1] and Norway imply a very much earlier glaciation, falling in the oldest Cambrian, or perhaps even pre-Cambrian, times. Still more recently, similar evidences of early Paleozoic glaciation in South Africa have been announced.

The climatic student seems therefore compelled to face oscillations within the known geologic periods, ranging from sub-tropical congeniality within the polar circles, on the one hand, to glacial conditions in low latitudes, on the other, and these *in alternating succession;* while neither of these oscillations was permitted to swing across the narrow limital lines of organic endurance. There is little doubt that the ocean, the daughter of the atmosphere, is one of the most potential agencies in controlling these oscillations. It is one of its possible functions in such regulation that invites our present attention.

Some of the regulating functions of the ocean have long been recognized. Certain less familiar ones have been brought under study in recent years by a few students independently. Schlœsing was perhaps the first to clearly recognize that the carbon dioxide of the ocean is an important agency in the regulation of the atmospheric content of this critical factor. As early as 1880[2] he advanced the

[1] Willis, *Third Year-Book*, Carnegie Institution (1904), p. 282.

[2] "Sur la constance de la proportion d'acide carbonique dans l'air," *Comptes Rendus*, Vol. XC (1880), p. 1410.

view that the carbon dioxide of the atmosphere is in equilibrium, not only with the free carbon dioxide absorbed in the sea water, but, through dissociation, with the second equivalent of carbon dioxide in the oceanic bicarbonates. The sum-total of such free and loosely combined carbon dioxide available at present as a possible supply for the atmosphere may be some twenty-five times the present atmospheric content. Schlœsing held that any depletion of the atmospheric content would be followed by emanation from the ocean, and any excess acquired by the atmosphere would be followed by oceanic absorption, and hence great changes in the atmospheric content would only be brought about by reducing or increasing the large sum-total of atmospheric and oceanic supply. This was a contribution of the first order to the problem of atmospheric regulation. It is necessary for a geologist, however, to recognize that the exchange, and even the equilibrium itself, are dependent on geological and physical conditions. At periods in which the oceanic bicarbonates were most abundant, the amount of free and loose carbon dioxide in the ocean may perhaps have reached 30 or 40 times the present atmospheric content, while, on the other hand, it may have fallen to a very low figure when the ocean was depleted of carbonates. It is necessary also to recognize that the diffusion of gases in water, so far as it is covered by experiment, is a slow process, and computation seems to show that the supply of carbon dioxide to the atmosphere might be much too slow to offset its consumption under certain geologic conditions, unless effectively aided by oceanic circulation. The active superficial circulation immediately assignable to the winds would aid somewhat, but its competency is limited. It was in an attempt to determine the functions of the deep-sea circulation in this interchange that the conceptions of this paper arose.

In an endeavor to find some measure of the rate of the abysmal circulation, it became clear that the agencies which influenced the deep-sea movements in opposite phases were very nearly balanced. From this sprang the suggestion that, if their relative values were changed to the extent implied by geological evidence, there might be a reversal of the direction of the deep-sea circulation, and that this might throw light on some of the strange climatic phenomena

of the past and give us a new means of forecast of climatic states in the future.

That the deep-sea circulation is now actuated dominantly by polar agencies is clear from the low temperatures of the abysmal waters, even beneath the tropics. It is a firm inference that cold waters creep slowly along the depths from the polar seas equatorward, where they gradually rise to the surface and return on more superficial routes. This is not, however, yet a matter of observation, and the courses pursued are unknown. It is perhaps more probable that they are gyratory or spiral and complex than that they are simple and direct.

The agencies that affect oceanic circulation include at least (1) wind, (2) atmospheric transfer, (3) differences of salinity, and (4) differences of temperature, including freezing and thawing. The earth's rotation, of course, modifies the currents, but does not actuate them.

1. The effect of the wind is superficial and familiar, and need only be considered here in so far as it affects the deep-sea circulation. Its currents constitute horizontal circuits, and their frictional effect upon the deep currents is probably slight and of a gyratory phase in the main. In so far as they are strictly horizontal, they doubtless favor equally poleward and equatorward movement in the abysmal waters. If there is a component of their sum-total that favors the piling up of waters in the polar regions, it must favor the present deep circulation. If the opposite is true, it must antagonize it. There seems no way at present to measure the relative amounts of these opposing tendencies. It is plausible enough to reason that the cold air from the polar regions would flow more largely at the base of the atmosphere than would the warmer air from the equatorial regions, and that the polar winds would thus antagonize the present abysmal circulation. But theoretical deductions are rarely sure-footed in these complex subjects. The balance of influence whatever it may be, is probably so slight as to be negligible.

2. We cannot here attempt to follow empirically the transfers of water by evaporation and precipitation, but general inspection seems to indicate the nature of the average effect. The saturation point of the atmosphere falls progressively from the equator to the poles, and

the actual humidity runs roughly parallel to it on the grand average. Poleward movement of the atmosphere leads therefore to a lower content of moisture; equatorward movement, to a higher. As the acquisition of moisture lags behind the capacity to hold it, it is a rather firm inference that precipitation exceeds evaporation in the high latitudes, and that evaporation exceeds precipitation in the low latitudes, on the grand average. The bearing of observational data is of the same import. The result of these ratios of precipitation and evaporation is a raising of the ocean surface by fresh waters in the polar regions and a lowering of it in the low latitudes accompanied there by concentration of saline constituents. Considered alone and ideally, this should give a slight equatorward gradient and a flow of fresh surface waters in that direction. These waters, however, mingle with the superficial sea waters, and involve a movement of these also toward the equator. So far as these affect abysmal movement, they antagonize the present circulation.

3. In so far as evaporation exceeds precipitation in the low latitudes, it results in an increased salinity of the superficial waters, and a tendency of these to sink and flow poleward to replace the salt waters carried equatorward by the fresh waters as just observed. If these were the only factors, it seems clear that the deep circulation would be poleward.

4. On the other hand, the lower temperatures of the high latitudes increase the density of the water, and tend to cause it to sink and flow equatorward. But the low temperatures affect primarily the superficial stratum which is freshened by the superior precipitation of the high latitudes, and both computation and observation show that cold fresher waters may float upon warmer saline waters. A large part of this cold superficial water flows away in surface currents to lower latitudes. The actual mode by which polar agencies control the deep circulation is therefore by no means so simple as it might seem.

There is ground to suspect that the formation and melting of ice is an important factor. In freezing, the salt and gases of the surface layer are largely forced out into the underlying layer. If the surface layer has an average degree of salinity, the underlayer is supercharged and, being also cold, must tend to sink. On the borders of

the ice-covered tracts, where the precipitation and melting are considerable, and where adjacent polar lands pour in much fresh water, the surface layers are so much fresher than the average sea water that the concentration of salinity by freezing does not overbalance the original freshness. But in those polar regions where there is little inflowage from the land, and where precipitation is slight and almost wholly snow, which accumulates on a previously frozen surface and absorbs most of its own summer melting, it is believed that a sufficient degree of saline concentration combined with depression of temperature takes place to cause an effective downward movement. This is believed to co-operate with diffusion and conduction in giving the lower body of polar waters the superior gravity which actuates the abysmal circulation. The sea immediately bordering Antarctica and that lying northwest of Greenland seem to furnish these conditions. Moss[1] and Krogh[2] have found that at times of northwesterly winds the air west of Greenland contains about double the usual content of carbon dioxide. This, I have suggested, may come from waters overcharged with it by the freezing of the overlying layer.

To a large extent the polar ice is carried to lower latitudes, and the waters arising from its melting do not redilute the concentrated waters, which are thus left free to pursue an independent course.

It is not to be inferred, however, that the deep-sea waters derived from the polar regions are superior in salinity to the waters of the evaporating tracts of low latitudes, but merely that by this concentration, conjoined with low temperature and modified by diffusion and mechanical mixture, water of superior gravity is derived, and that this controls the abysmal circulation.

Dr. Otto Pettersson, in an elaborate article, supports by experiment and observation the theory of Bjerknes, that the melting of the polar ice also promotes circulation, both superficial and deep-seated; but I can only make reference to this here.[3]

A survey of the existing temperatures and salinities of the ocean

[1] Moss, "Notes on Arctic Air," *Proceedings of the Royal Dublin Society*, Vol. II (1880).

[2] Krogh, "Abnormal CO_2 Percentage in the Air of Greenland, etc.," *Meddelelser om Grönland*, Vol. XXVI (1804), pp. 409–11.

[3] "On the Influence of Ice-Melting on Oceanic Circulation," *Geographical Journal*, Vol. XXIV (1906), pp. 285–333.

makes it clear that the battle between temperature and salinity is a close one, and that no profound change is necessary to turn the balance. The combined results of the many polar expeditions have shown that in the high latitudes of both hemispheres there is a superficial sheet of water 200–300 meters deep that is colder, but lighter, than that below, because it is fresher. It floats upon a warmer, more saline body of water below. This has been specially demonstrated by the investigations of Nansen.[1] This layer of coldest water moves to lower latitudes superficially in the main, showing that coldness alone is not determinative.

In the open Pacific and Indian Oceans hydrostatic equilibrium must be very closely maintained, because of the slight resistance to adjustment. It is shown by the charts of Dr. Alexander Buchan[2] that the concentrated warm saline waters form inverted cone-like masses that reach downward 4,000 feet or more. It thus appears that they lie in the same horizons as great masses of colder waters which their salinity must counterbalance. Less striking phenomena of similar import mark the evaporating areas of the north and south Atlantic. The equatorial tracts of freshened waters arising from high precipitation are scarcely traceable to half the depth. This seems to imply that in the low latitudes increased density due to evaporation is more potent than freshening precipitation, in harmony with theory, as already set forth, and that the density due to salinity is not greatly overmatched by the low temperature density of the Antarctic regions, from which the Pacific and Indian Oceans are not separated by appreciable barriers.

An interesting illustration of the close balance between salinity-density and temperature-density is presented by the saline waters that issue from the Mediterranean, in which evaporation is in excess of combined precipitation and inflow from adjacent lands. As a result, the concentrated waters that form the deeper body of the Mediterranean creep out through the bottom section of the Straits of Gibraltar, while the upper section is occupied by a compensating

[1] Fridtjof Nansen, *The Norwegian North Polar Expedition*, 1893–1896, *Scientific Results;* Vol. II, "Oceanography of the North Polar Basin."

[2] Challenger Reports, *Summary of Results*, Part II, Appendix, "Report on Oceanic Circulation."

inflow from the Atlantic. Although the Straits are shallow, the out-creeping current does not appear in the upper horizons of the adjacent Atlantic waters, according to Buchan's charts, but descends to depths of 3,000 to 5,000 feet before it finds a horizon of density-equilibrium. It then spreads westerly in a great spatulate wedge across the North Atlantic, and occupies the larger part of its area between the depths of 4,000 and 5,000 feet. It is warmer and more saline than the normal oceanic waters at its horizon, and lies on colder but less saline waters below.

These and similar phenomena point to a notable closeness of the balance between the density-effects of salinity and of temperature respectively. More saline but warmer waters both overlie and underlie less saline but colder waters. On the whole, however, at present, the temperature effects are dominant and cold waters occupy the abysmal depths of all the great oceans.

A comparative computation of salinity-effects and of temperature-effects on density, from such data as are now available, leads to a similar conclusion relative to the closeness of balance between the opposing agencies; but this cannot be entered upon here.

Now, as previously remarked, the geological record gives good evidence that in the majority of known periods the temperatures in the polar regions were sub-tropical or warm temperate. Freezing must apparently have been a trivial factor, if not quite absent, and low temperature was robbed of its chief densifying effects. Evaporation in the zones of descending air-currents in low latitudes must apparently have been operative, in some degree at least, to furnish the geological agencies which the record implies. Deposits of salt and gypsum in not a few periods testify directly to regional aridity. The most marked of these are, to be sure, referable to the periods of glaciation, but many of them have no such assignable association.

In these periods of warm polar temperatures there is reason to believe that the polar temperature-effects fell below the low-latitude concentration-effects, and that therefore the deep oceanic circulation was actuated by the dense waters of the evaporating tracts. These may then be supposed to have slowly descended and crept poleward, acquiring a trivial amount of heat from the earth's interior, and losing some to the waters above, but substantially maintaining

their temperatures until they rose to the surface in the polar regions and gave their warmth to the atmosphere. Aided by the enshrouding mantle of vapors that must have arisen from such a body of water, it is conceived that the mild temperatures requisite for the maintenance of the recorded life through the polar night may have been thus maintained.

If this be granted, however, it is wise to note that this is not a radical solution of the climatic problem, for a fundamental cause for the conditions that brought on freezing at one period and prevented it at others is prerequisite to the postulated influence of these in the reversal of the abysmal circulation. At the best, our suggestion offers only an auxiliary agency in the control of secular climates. Some more fundamental agency or agencies must be sought.

THE SERRA DO ESPINHAÇO, BRAZIL

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The name Serra do Espinhaço ("Backbone Range") was introduced into geographical literature in 1822 (1) by the founder of Brazilian geology, Wilhelm von Eschwege, as a comprehensive term for the various orographic units that form a great watershed between the rivers flowing directly to the Atlantic and those that discharge first into the Uruguay, Paraná, and São Francisco. By modern usage, and in fact by the subsequent usage of Eschwege himself, the name has, however, been practically limited to the section of this watershed corresponding to the São Francisco basin, the greater part of that corresponding to the Paraná basin being known as the Serra da Mantiqueira, while the remainder of this section and the one corresponding to the Uruguay basin are considered as forming parts of the Serra do Mar range. As thus limited, the name, though robbed of much of its pristine importance and appropriateness, is applied to a well-marked orographic feature distinguished by special topographic, geologic, and tectonic characteristics.

Some of the most distinctive topographic and geologic features of the range are well set forth by Eschwege in his detailed descriptions of his various journeys in the gold and diamond districts (2) comprised in the section extending from Ouro Preto to Diamantina, the occurrence of these minerals being of itself one of the leading characteristics of the range. Thus he contrasts the greater mean elevation (1,000^{m}± with peaks rising to 1,500–1,800^{m}), the general plateau character with abrupt margins, the bald and rugged aspect of the peaks and minor ridges, and their general north-south trend, and the predominance of schistose rocks (especially quartz and ferruginous schists), with the lower altitude, gentler and apparently systemless topography ("like a storm-tossed forest sea") and predominance of crystalline rocks (principally gneiss and granite)[1] that characterize

[1] Eschwege had a special crystalline-chemical hypothesis of his own (set forth in detail on pp. 11 ff. of his *Gebirgskunde*) regarding the mode of formation of what

the adjacent zones, particularly the one lying to the eastward. The tectonic features of the range have, on the contrary, scarcely been touched upon by him or his successors.

Owing to its wealth of gold and diamonds, the southern section of the range, from Ouro Preto to Diamantina, has been frequently visited and described, with attempts to give an idea of its geological characteristics; but, with the exception of the writings of Eschwege, Spix and Martius (3), Helmreichen (4), Henwood (5), and Hussak (19), but little is to be found in the somewhat voluminous (as compared with other parts of Brazil) literature relating to this region that, from a geological point of view, is comprehensible, or, being so, is of permanent value. The remaining sections and the regions on either side are almost a *terra incognita* from both a topographic and a geologic point of view, and, as in all other parts of Brazil, the lack of reliable maps is an almost insuperable obstacle to detailed geologic studies. The present sketch is based on a few flying trips to the above-mentioned gold and diamond regions, a hurried and partial examination of the diamond-bearing section in the state of Bahia, a boat trip on the river São Francisco and its tributary, the Rio das Velhas, and an excursion into the region of the middle Jequitinhonha, which, however, did not extend as far as the eastern margin of the Serra do Espinhaço region. The observations that could be made on these hurried trips, supplemented by the meager gleanings to be found in the literature relating to the region, are manifestly inadequate for more than the most general treatment of the subject.

The Serra do Espinhaço, as now understood, constitutes a zone with a width of about 50 to 100 kilometers, and a mean elevation of over 1,000^{m}, characterized by rugged topographic features, and rising with abrupt margins a few hundred meters above the lower regions of more uniform topography on either side. It extends in

in his time were known as the primitive rocks, among which he included, as a second division, the bedded arenaceous and argillaceous rocks of the Serra do Espinhaço. He did not admit a succession of sediments among them; he did not attempt to subdivide them into series. The most unfortunate result of this point of view was the lumping-together of all the quartzose rocks of the region under the general name of "itacolumite," which has been an incubus on Brazilian geological studies. Being an acute geological observer, he did not fail to note evidences of the existence of two unconformable series of beds among the rocks so classed, but, withheld by his theory, he did not give these observations their due importance.

almost perfect parallelism with the coast-line and with the river São Francisco (above the great bend at Cabrobó), with a general northerly trend from about latitude 20° 30″ to about latitude 9°, where the river São Francisco, after making a sharp bend to the southeast, cuts through the range or, more probably, flows past its northern end. Throughout this extension of over 1,000 kilometers, this zone forms the eastern rim of the São Francisco basin, which receives the drainage of its western portion, while its eastern drainage goes directly to the Atlantic through the rivers Doce, Jequitinhonha, Pardo, Rio de Contas, Paraguassú, Itapicurú, and Vasabarris. In the upper part of the basins of the Rio das Velhas, Jequetinhonha, and Paraguassú, and to a less extent in that of the Rio de Contas also, the drainage courses correspond approximately with the north-south trend of the serra, while, after escaping from it, the Rio das Velhas and the Jequitinhonha flow for a considerable distance in general parallelism to its margins. As certain structural features are more apparent in the northern than in the southern section of the range, our examination can best be made from north to south.

The São Francisco, at some 80 kilometers below the great bend at Cabrobó, where it changes from a northeast to a southeast course, enters a zone of sandstone country which lies in the line of prolongation of the Serra do Espinhaço, though it is somewhat doubtful if it should actually be included in that range. This zone extends from near the mouth of the small river Pajahú to near the great cataract of Paulo Affonso, with a width, along an east-west line, of at least 50 kilometers, while away from the river the width appears to be much greater. The river, which above this zone flows over a bed of gneiss and granite, enters the sandstone belt at an elevation of about 330^{m} and leaves it at an elevation of about 300^{m}, to again flow over gneiss, granite, and syenite, in which it has excavated a deep canyon that contains one of the most notable of Brazilian cataracts. The sandstone therefore rests on a nearly horizontal base of truncated crystalline rocks (a peneplain ?) with a mean elevation of about 300^{m}, and rises in table-topped hills and ridges on each side to about an equal elevation, or approximately 600^{m} above the level of the sea.

The sandstone is moderately hard, usually coarse-grained, with frequent inclosed pebbles, which in some layers become sufficiently

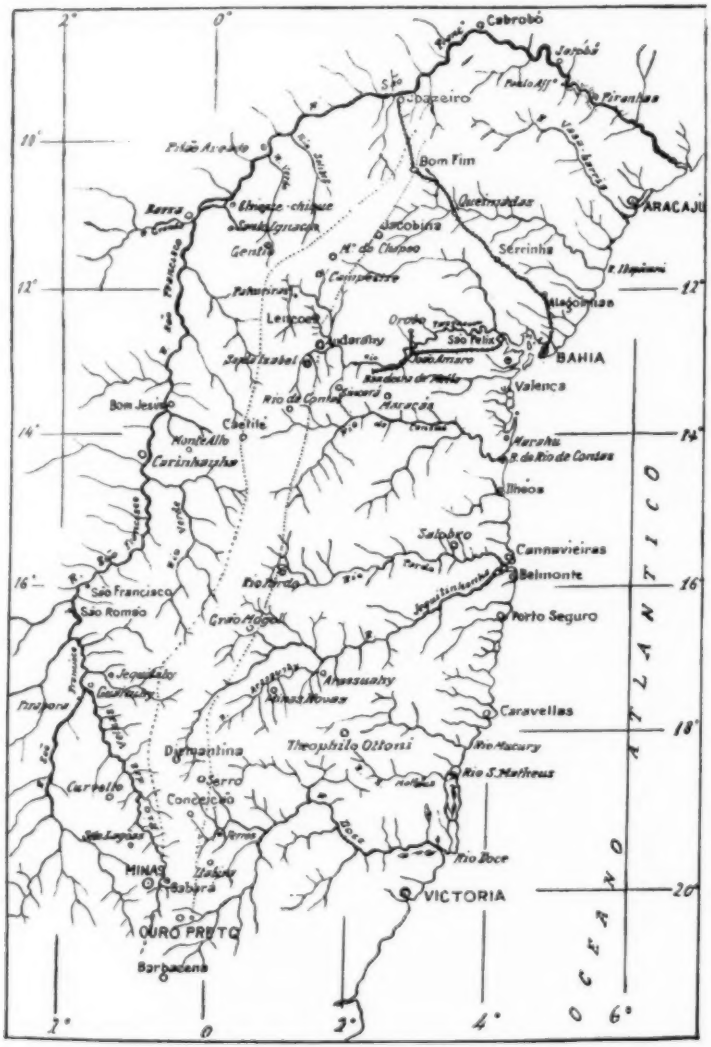

FIG. 1.—Sketch map of the region to the east of the river São Francisco. (The otted lines show the approximate lim'ts of the Serra do Espinhaço belt.)

abundant to constitute a conglomerate. The rock is frequently argillaceous, and thin layers of marly shale appear in which at two points (Atalho and Angico, about 6 kilometers apart) I found fossil woods, cyprids, and bones, teeth, and scales of fishes and reptiles (8, 9, 10). The small collection made here was unfortunately lost, but on the occasion of making it I had the strong impression of a close relationship with the fresh-water Cretaceous fauna of the neighborhood of Bahia, based on the general aspect of the fossils, and especially on scales that I identified as *Lepidotus*. In this connection it is to be noted that the famous fossil fishes (including a *Lepidotus*) of the vicinity of Jardim, in the state of Ceará, occur at a distance of about 200 kilometers to the northeast, in front of the base of a sandstone table-land which may readily be presumed to be connected with that of the margins of the São Francisco. The sandstone beds appear at first sight to lie horizontally, but at a number of points moderate northerly dips (seldom more than 10°) were observed, but no distinct evidence of folding could be detected.

The railroad from Bahia to Joazeiro on the river São Francisco affords an undoubted section across the Serra do Espinhaço belt which is crossed near the town of Bom Fim (formerly Villa Nova da Rainha). The road, starting from sea-level at Bahia, runs for 122 kilometers in a general northerly direction to Alagoinhas (alt. 137^{m}) through a country composed of soft Cretaceous and Tertiary strata that have been quite fully described by Hartt, Rathbun, and myself (6, 7). From this point the narrow-gauge prolongation runs in a general northeasterly direction for 452 kilometers, crossing the Serra do Espinhaço belt between kilometers 320 and 370, with a summit level of 683^{m}, and ending at Joazeiro at an elevation of 372^{m}, the terminal station being only slightly above the high-water level of the São Francisco at this point. In a trip over this line the following car-window observations could be made.

From Alagoinhas the road ascends for 60 kilometers over horizontal beds of soft sandstone to an elevation of 406^{m}. Up to the 200^{m} level the beds are quite argillaceous and gritty, and a water-bearing horizon occurs here which probably marks a break in the stratification, since the beds above this level are more sandy and porous, generally deeply stained by oxide of iron, and in general of

quite different aspect from those below. At kilometer 29 (elevation 281^{m}), near the station of Uruçanguinhas, a soft ochrous shale, containing beautifully preserved fossil leaves, appears in a cutting. Collections of these fossils were remitted some years ago to Sapota and Ettenhausen, but both unfortunately died before reporting upon

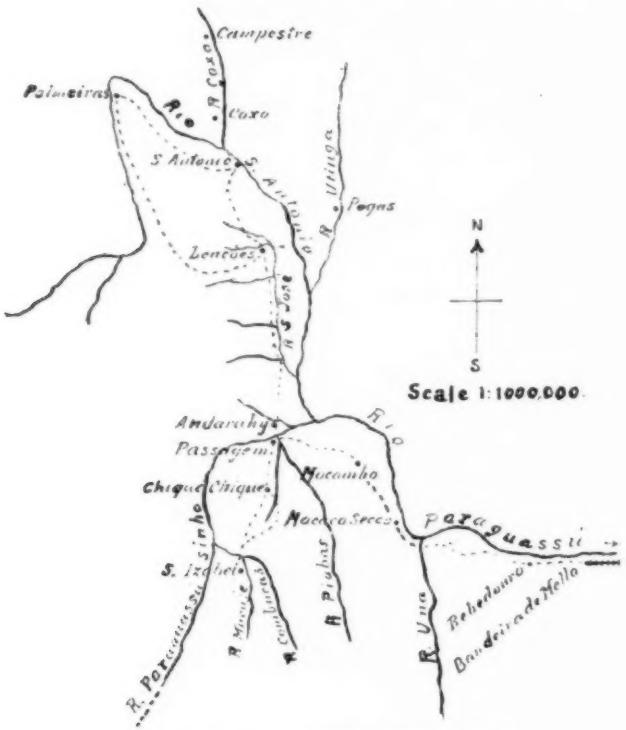

FIG. 2.—Sketch map of upper Paraguas.ú bas'n.

them. It is understood, however, that they were considered to be of late Tertiary, probably Pliocene, age. The western face of this Tertiary plateau presents a thickness of about 80^{m} of strata, as gneiss appears in a stream-bed at kilometer 85 at an elevation of 322^{m}. From this point to Jacuricy station (kil. 245) the road crosses a plateau of a general elevation of about 400^{m}, dotted with detached

knobs and ridges. The soil cap is generally thin, gneiss and granite rocks appearing underneath it. With these occur considerable stretches of a black schistose rock, which is presumed to be mica or hornblende schist. A considerable part of this section of the road is along the watershed between the Paraguassú and Itapicurú, descending afterward to the valley of the latter. To the westward of this comparatively level section rises (kil. 257; alt. 343^{m}) the Serra de Itiuba, a bold ridge of red granite estimated to be about 800^{m} high. The road crosses it in a gap at an elevation of 437^{m}, and descends to the river Itapicurú (kil. 280) at 354^{m}, and then ascends over gneiss and granite to the city of Bom Fim (kil. 320), on the flank of the Serra do Espinhaço, at an elevation of 548^{m}. On the ascent to the summit (kil. 355; alt. 683^{m}) the cuttings are in granite to kil. 333, where flaggy quartzites begin to appear and continue, with occasional interruptions of granite, to Angicos station (kil. 383; alt. 487^{m}), which is a little beyond the western base of the serra. From Angicos to the end of the line at Joazeiro (kil. 450; alt. 372^{m}) the country is a gradually sloping plain, so slightly accidented that for 60 kilometers the road has been laid out on a perfectly straight line. Scattered knobs and ridges of granite, gneiss, and quartzite rise abruptly above the general uniform level. The rocks seen from the foot of the Serra do Espinhaço to kil. 391 (alt. 490^{m}) are gneiss and granite, with occasional outcrops of quartzite. From this point to kil. 430 (alt. 416^{m}) the surface rock is a whitish limestone in horizontal beds, and of only a few meters' thickness. The aspect of the rock is that of a fresh-water deposit, and though no fossils could be found, it is presumed to be of Tertiary, or possibly Quaternary, age. A similar limestone is known to occur higher up the river in the neighborhood of Chique-Chique, where it appears to cover a considerable area. Along the last 20 kilometers of the road gneiss and granite reappear.

A recent excursion to the diamond region of the upper Paraguassú basin gave me an opportunity to examine the section characteristic of the valley of that river. The trip was made by the Bahia Central Railroad to its terminal station, Bandeira de Mello, situated about 100 kilometers, by the river, to the east of the point where it escapes from the serra at Passagem (see annexed sketch map), the remainder being made on mule-back. The railroad, starting from São Felix

near the mouth of the river, rises at once with a heavy grade to the top of a gneiss plateau with a general elevation of 200 to 300^{m}, over which it runs in a line parallel to the river and about 20 kilometers to the southward of it to kil. 165, where it again meets the river and follows its margin to the terminal station at kil. 259. The gneiss plateau away from the river is remarkably level, but dotted with isolated knobs and ridges that for the most part seem to be composed of granite, which also appears in numerous bare ledges

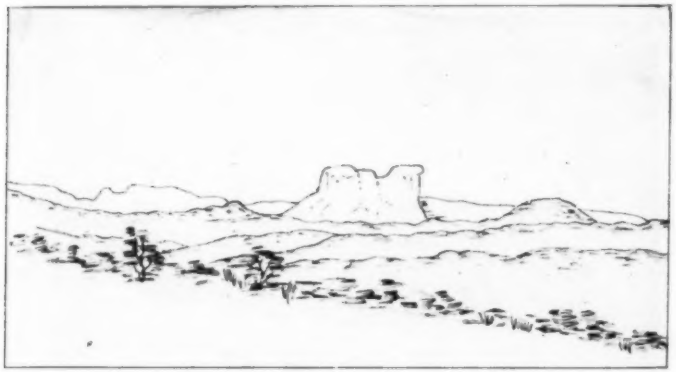

FIG. 3.—Profile near Lençoes.

that do not rise perceptibly above the general level of the plain. Except in the eastern part, about the headwaters of a small river draining directly to the sea, and apparently in a zone of abundant rainfall, the soil-cap is very thin, often lacking. In this respect, and in the general evenness of the surface, the western part of this plain, like those above described along the São Francisco road, seems to offer a good example of the formation, under arid conditions, of plains by the truncation of strata that normally would present a strong relief.[1] The section accompanying the river is bordered by gneiss

[1] See discussion of subaërial denudation in an arid climate, by Professor W. M. Davis, in *Journal of Geology*, No. 5, 1905. No reliable data regarding the mean annual rainfall in the districts here considered could be obtained, but it is tolerably certain that it is less than a meter, and that the minimum is often less than half a meter. With the exception of the Paraguassú and the streams of the Serra do Espinhaço belt, all streams dry up, or become reduced to strings of pools during several months of each year.

and granite rising a few hundred meters above the level of the river, and here the traveler cannot form an adequate idea of the general topographic features of the region, which, however, appears to be considerably higher than that along the first section of the line. The terminal station, Bandeira de Mello, is at an elevation of about 300^{m} above the level of the sea, in the midst of gneiss and granite hills that rise about as much higher.

About 20 kilometers to the westward of the end of the railroad begins a region of sedimentary rocks that includes the whole of the

FIG. 4.—View of Santa Isabel do Paraguassú.

upper part of the Paraguassú basin. Near the river this region begins at Bebedouro with an escarpment of sandstone and limestone rising some 250^{m} above the level of the stream to a plateau of a mean elevation of about 600^{m}. Behind this rises a second plateau of sandstone to a mean elevation of 1,000^{m} or more, and constituting the Serra do Espinhaço proper, or, as it is here known, the Chapada Diamantina ("Diamond Table-Land"). To the northward of the Paraguassú the margin of the serra is marked by the river São José, which escapes from it near Lençoes and flows along its base. On the south side of the Paraguassú this margin makes an offset to the eastward as far as Mocambo, thus causing a great bend in the river,

and from there extends southward in a high ridge between the small rivers Piabas and Una. This upper sedimentary part of the Paraguassú basin is of rectangular shape, with its longest axis lying in a north-south direction, and thus perpendicular to the general west-east course of the middle and lower portions. It is characterized topographically by secondary valleys extending from south to north and from north to south, which unite their waters below Passagem, and where the main valley assumes a general easterly direction.

The geological structure of the first and lower plateau is fairly well seen along the road from Bebedouro to Mocambo. At the first

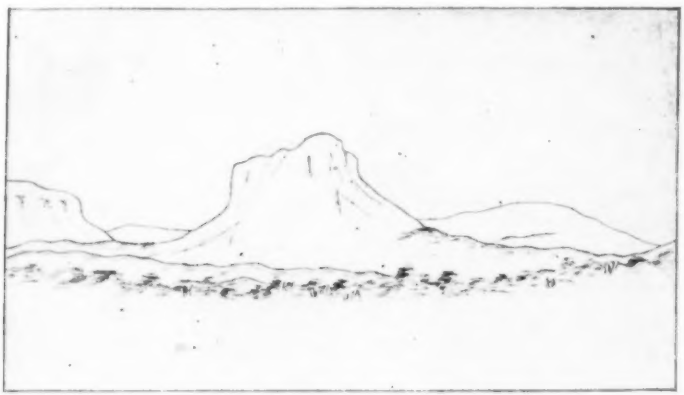

FIG. 5.—Profile near Santa Isabel.

locality a fine escarpment, that extends southward as far as the eye can reach, rises abruptly from the right bank of the river to an estimated height of 250^{m}. The base is composed of a horizontally bedded, coarse, reddish sandstone. On a trail leading back among the hills the sandstone is seen to rise to about 20^{m} above the river, intercallations of micaceous sandy shale appearing near the top. The section is then interrupted for a further rise of 40^{m}, and then comes a magnificent bluff of light-blue flaggy limestone about 40^{m} high. Some of the layers are full of cherty nodules, which on weathering out of the rock afford a means of tracing it where concealed by a soil-cap. At the Cachoeira do Funil, 6 kilometers above Bebedouro, a similar escarpment, that stretches away to the northward, appears

on the northern side of the river, and the base of the sandstone is seen to consist, for a thickness of a few meters, of a coarse conglomerate containing pebbles and bowlders of gneiss and granite. At one point the conglomerate is seen to rest on granite. The road then ascends, over a chert-strewn trail, a table-topped ridge known as the Serra das Araras, which is said to abut on the river in a fine limestone bluff. On the top of this ridge the aneroid indicated an elevation of 575^{m}. Small outcrops of limestone occur on the western descent to the river Una, where just below the bridge is another limestone bluff 35^{m} high. The beds here, as at Bebedouro, have a slight westerly dip of 5–10°. On the ascent from the river Una the road passes over about 100^{m} of strata above the limestone, but no rock *in situ* appears. Cherty nodules appear in three distinct zones, and the underlying rocks are presumed to be shales and sandstones with intercallations of limestone.

A diligent search for fossils both at Bebedouro and Rio Una was fruitless, although the limestone seems very favorable for preserving them. Limestone is reported to occur near the head of the Rio Una, and the valley of this small river is presumed to be almost exclusively occupied by this series, which also appears to the northward of the Paraguassú in the valley of the lower Santo Antonio, and Utinga in the neighborhood of Pegas. So far as could be made out, this series is from 200 to 250^{m} thick, and is practically undisturbed, or at all events much less so than the strata in the adjacent Serra do Espinhaço zone. About a quarter of the thickness, and perhaps much more, is composed of limestone which is characteristically cherty, at least in many of its layers.

From Mocambo to Passagem the road passes, at an elevation of 600^{m}, over a ridge that rises considerably higher to the southward. The rather unsatisfactory rock exposures consist of sandstone, in places lying horizontally, in others with a moderate dip to the eastward or to the westward. The section along the road seems to be across the expiring end of a fold which to the southward forms a high ridge known as the Serra do Sincorá, on the eastern margin of the Serra do Espinhaço plateau. An appearance, as seen from a distance, of synclinal structure in the valley of the Piabas, on the western flank of the supposed fold, confirms this interpretation.

The serra front between Chique-Chique and Lençoes is constituted by a heavy series of sandstone beds dipping eastward at an angle of about 30°, and rising from a minimum elevation of 330^{m}, in the bottom of the valley at Passagem, to a crest line of 1,100–1,200^{m}. Passing over the crest on the road from Chique-Chique to Santa Isabel, flat-lying portions and westerly dips were observed. Westerly dips also occur on the road leading northward from Lençoes to Palmeiras, and about the latter place. The details of the structure could not be worked out, but it is evident that a great sandstone sheet is here bent into broad anticlinal folds. Apparently the main fold of the district begins with a narrow end to the northward of Lençoes, broadens out southward, and narrows down again near Santa Isabel, where it becomes confused with other folds. The combined valleys of the São José and Chique-Chique are excavated

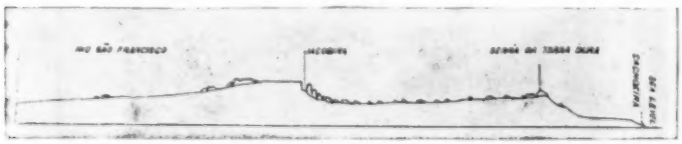

FIG. 6.—Profile of the route from the São Francisco to Bahia, by Mr. J. A. Allen.

along the strike of the softer upper beds of the eastern wing of this fold, laying bare a group of harder quartzitic and conglomeratic beds that occur near the middle of the series. The most prominent member of this group is a thick bed of coarse conglomerate that is diamond-bearing, and in consequence of the topographic disposition of the strata, the entire serra front from Lençoes to Chique-Chique is marked by an almost continuous line of active or abandoned diamond-washings.

Over the top of the plateau, which, as already stated, has a mean elevation of 1,000^{m} or more, the sandstone sheet is much broken up into detached blocks, as shown in the annexed outlines traced from photographs, and in the view of the town of Santa Isabel which I owe to Dr. Henry Furniss, United States consul at Bahia. The escarped margins of these blocks, and other phenomena in the district, are at times suggestive of faulting, but, however important this may have been in determining minor features, it is evident that

the main tectonic features of the region have been produced by folding and denudation.

The sandstone sheet, estimated to be from 400 to 500^{m} thick, consists of a lower flaggy, reddish portion, well seen in the blocklike hills about Santa Isabel, succeeded by a coarse conglomerate that passes to a whitish sandstone with scattered pebbles and patches, and layers of conglomerate, and finally to argillaceous sandstones and sandy shales. The conglomerate, where seen in contact with the lower red sandstone, contains large fragments of this rock that indicate a time-break and unconformability, at least of overlap,

FIG. 7.—The Tombador (Tumble Down) near Jacobina, by Mr. J. A. Allen.

between the two. Some of the sandstone layers next to the conglomerate are very hard and quartzitic, but in general both members of the series are unmetamorphosed. The lower member may take the name of the Paraguassú group, as it is especially well developed in the vicinity of Santa Isabel (or São João) do Paraguassú. The upper member may appropriately be denominated the Lavras group, as its conglomerate member is undoubtedly the principal, if not the only, repository of the diamonds that have given the popular name of Lavras ("Washings") to the whole district. The thickness of the Paraguassú group can be estimated with approximate accuracy at about 250^{m}; that of the Lavras group cannot be so closely calculated, but it is probably about the same.

With the exception of the sandstone blocks above mentioned, the pebbles of the conglomerate, seen by the thousands in hundreds of square meters of clean-cut fractures passing through them, are exclusively of quartzite. These represent an older formation, to be mentioned farther on, which is known to occur in other sections of the Serra do Espinhaço and which may be presumed to occur also in the Paraguassú section to the westward of the region here described. The central portion of the range in this section and the country to the westward are very imperfectly known, but the recurrence of diamond camps justifies the presumption that the Lavras conglomerate

FIG. 8.—View on the gneiss plain of Bahia, by Mr. J. A. Allen.

recurs frequently, through folding, over a great part of it. The westernmost of these camps is in the Serra de Assuruá, a detached mountain ridge near the river São Francisco. Burton (20), who visited it, mentions the occurrence of a coarse conglomerate, which he compared to the Old Red Sandstone of Scotland.

Another section, intermediate between the two above described, across the range and the adjacent country on each side, is given in an interesting note by Mr. J. A. Allen, published in Hartt's *Geology and Physical Geography of Brazil.* Mr. Allen's route was from Chique-Chique on the São Francisco to Bahia, passing by Jaeobina, and thus about 100 kilometers to the southward of the first railroad line above described. His profile of the route and sketches of characteristic line of travel as being essentially over three distinct plateau

regions, a limestone plateau to the westward, a sandstone one in the central or Serra do Espinhaço region, and a gneiss one to the eastward. The last presents a remarkably level aspect, being apparently everywhere of nearly uniform altitude, but is dotted with isolated, abruptly rising points and knobs, as shown in the annexed sketch. The soil-cap is thin, and often entirely absent, over areas of several acres in extent.[1] In the serra zone a horizontal sandstone gives rise to a beautiful level, grassy plain occupying the summit of the watershed. To the eastward this table-land breaks down abruptly in precipitous cliffs, to the lower gneiss country, but to the westward the slope is more gradual to the limestone plain, and across this to the São Francisco. Above the generally level surface of the latter rise irregular pinnacled hummucks and low serras. The limestone is highly inclined, and in one place was seen lying unconformably under horizontal beds of sandstone that stretched away southward like a vast level floor. Near the western base of the serra two large hills of hornstone or chert were crossed.

From the general topographic features of the Serra do Espinhaço zone it would be natural to assume that the sandstone sheet of the Jacobina region should be considered as the northern prolongation of that of the upper Paraguassú district, which, with its characteristic diamond contents, certainly extends northward as far as Morro do Chapeo, or about two-thirds of the intervening distance between Lençoes and Jacobina. In this case it has remained unfolded in the northern end of the zone—a seemingly improbable hypothesis; or the evidences of folding escaped Mr. Allen's observation, which also seems unlikely, as his sketch confirms his description. Moreover, unfolded sandstones occur in the region at no greater distance away than those of Lençoes, as shown in the annexed sketch by Dr. Theodoro Sampaio of a table-topped ridge, $750 \pm^{m}$ high, above

[1] Mr Allen describes singular holes in the rocks of this region, which are usually filled with water and known as *caldeirões* ("pot-holes"), and states that nearly all of a considerable number examined prove to be genuine pot-holes, some of which were of great size. These are probably of the same nature as the caverns, looking like gigantic swallows' nests in a clay bank, seen on the granite knobs along the Bahia Central Railroad. So far as could be judged from distance, these are due to a peculiarly localized action of disintegration. Those seen, however, were on the sides of hills and would not hold water.

Joazeiro and close to the São Francisco, and which he informs me is composed of horizontal beds of sandstone and conglomerate overlying inclined quartzite. The topographical features and the elevation of this ridge, as of others in the vicinity, are suggestive of the Cretaceous plateaus of the lower São Francisco and of the states of Ceará and Piauhy, and there is nothing improbable in the hypothesis that these (coming from Piauhy) extend into this region. This hypothesis would become a certainty if one could accept unreservedly the statement of M. Liais (21) that at a place called Engenho, somewhere near the western base of the Jacobina serra, he found nodules of argillaceous limestone containing scales of *Lepidotus*, a ganoid tooth, and gasteropod shells which he identified as *Paludina* and *Planorbis*. These fossils, with the exception of the shells, are

FIG. 9.—Serra do Encaibro (Ridge Pole), seen from the river São Francisco.

very suggestive of those of the fish-bed of Ceará, which have been carried far and wide over the country, and in part probably over this very road. On the other hand, experience elsewhere has shown that the statement of this author must be taken with caution. Still there is no inherent improbability in the hypothesis that the fossils may have been found *in situ* as stated.

In the region to the west of the serra Mr. Allen seems to have generalized his observations on inclined limestones to all of those seen along the road. It is certain that horizontal beds of limestone like that above mentioned in the vicinity of Joazeiro occurs at and about Chique-Chique, and, as in other parts of the São Francisco basin, it is probable that both horizontal and inclined limestones occur among the older rocks. The chert-strewn hills are suggestive of the series to the east of the serra in the Paraguassú basin.

Another line of travel across the Serra do Espinhaço region in the state of Bahia lies to the southward of the Paraguassú route above described, and passes by Maracás, Sincorá, Villa do Rio de Contas, Caetité, and Monte Alto, to Caranhanha on the river São Francisco.

Some interesting information regarding the topographic and geologic features of this route can be gathered from the narrative of Spix and Martius (3), and from the report of Dr. Theodoro Sampaio (22). The road, starting from São Felix, is for some distance nearly coincident with the railroad line above described, and over a gneiss plain of moderate elevation. It then rises to the top of a higher gneiss and granite plateau at Maracás, at an elevation of about 1,000^{m}, that occupies the watershed between the rivers Paraguassú and Rio de Contas. This plateau, according to Dr. Sampaio, breaks down to the westward in a wall-like face about 350^{m} high which overlooks an undulating region with detached hills that intervenes between it and the Serra do Sincorá, the eastern front of the Serra do Espinhaço plateau. This region is also composed mainly of gneiss and granite, but about the headwaters of the Rio Una a zone of reddish shale and ash-colored limestone intervenes between the crystalline rocks and the sandstone and conglomerate of the Serra do Sincorá. The Serra do Espinhaço section of the road, extending from the south end of the Serra do Sincorá to beyond Caetité, is mainly over a highly inclined series of quartzites and argillaceous schists, which Spix and Martius identified with those of the gold districts in Minas Geraes (this region is also auriferous), with occasional exposures of gneiss, micaschist, and granite. To the right of the road, and forming the highest points of the region, these older rocks are overlain by a conglomeritic sandstone, which Spix and Martius referred to the Rothtodtliegende, and which evidently represent spurs and outliers of the sandstone sheet of the adjacent upper Paraguassú basin. The western face of the plateau, known by the local name of "Serra Geral," is abrupt, but of no great altitude (850^{m}) at the watershed near Caetité, where it is composed of gneiss. To the west of the mountain front the road is over a nearly level plain of truncated granite, gneiss, quartzite, and limestone rocks, but with isolated knobs and ridges rising above the general level.

To the south of the Rio de Contas road to Grão Mogol, in the state of Minas Geraes, a distance of about 300 kilometers, but little is known of the Serra do Espinhaço plateau beyond the fact that diamonds occur in several localities. For the section about the northern headwaters of the Jequetinhonha in the neighborhood of

the diamond-mining town of Grão Mogol, Helmreichen (4) has given an excellent description, accompanied by a geological section of his route from the middle Jequetinhonha across the serra to the Rio Verde.[1] According to this description and section, the Serra do Espinhaço is here a broad mountain plateau, which rises abruptly above lower plateaus on either side. The eastern plateau consists of truncated strata of micaceous gneiss and micaschist with, near the foot of the serra, intercallations (outlyers?) of quartzite; the western one, of truncated inclined beds of grauwacke and limestone. The central, or Serra do Espinhaço, plateau consists of an undulating central portion of various schists, including gneiss and quartzite, with patches of granite and hornblende rock, above which rise ridges of quartzite which is frequently conglomeritic,[2] and in which diamonds occur—a circumstance that has given great importance and interest to the locality of Grão Mogol. From specimens that have come to hand, and from information given by two excellent geological observers, Drs. Francisco de Paula Oliveira and L. F. Gonzaga de Campos, it is clear that (as in 1882 I predicted would eventually prove to be the case), (12), the section at Grão Mogol is essentially identical with the one at Diamantina, which will now be considered.

In the neighborhood of Diamantina the range also consists of a broad mountain plateau, with a mean elevation of 1,200 to 1,300^{m}, rising abruptly above lower plateaus on either side. In the one to the eastward truncated strata of gneiss and micaschist, full of quartz veins that are frequently auriferous, have been leveled up to about the 900^{m} line by horizontal beds of soft sandstone which cover an extensive area in the valleys of the Jequetinhonha and its tributary, the Arassuahy, forming table-topped hills and ridges between the valleys which have been cut from 200 to 300^{m} below the level of the plain. Hartt, who visited this region in 1865 (6), correlated these

[1] This section is along a zigzag line which in part accompanies the strike of the strata. Thus, while it gives a transverse section of the range, it fails to give an accurate idea of the relative width of the different zones.

[2] Helmreichen, following Eschwege, lumped all the quartzites of the region together under the name of "itacolumite," and interpreted the pebbles in the conglomerate as concretions or segregations. For this reason, although he clearly described and figured evidences of unconformability between two distinct series of quartzites, he did not interpret them as such, and thus his otherwise excellent description of the region loses much of its value from a geological point of view.

beds with the Tertiary series of the coast, and cited them as evidence of a general uplift to the amount of about 1,000^{m}. There is, however, no evidence that they are of marine origin, and it seems much more probable that they were deposited in a closed inland basin, which extends for a long distance down the Jequetinhonha valley, but is probably cut off from the lower-lying coast Tertiary series by a high zone of older rocks. In this case the evidence of uplift is given by the depth to which the valleys have been excavated below the surface of these beds, rather than by their elevation above the level of the sea, and its amount ($250 \pm ^{m}$) accords fairly well with that indicated by the coast Tertiary beds themselves.[1] The sandstone beds are often quite thin, and probably nowhere more than 100^{m} thick.

The plateau to the west of the Serra do Espinhaço, with a general elevation of 800 to 900^{m}, also shows truncated folds, but the strata here consist of shales, sandstone, and limestone thickly threaded with quartz veins. Farther west, and near the São Francisco, appear table-lands of horizontal sandstones and shales of about 800^{m} elevation. Silicified dicotyledinous wood occurs in some of these beds, which are presumed to be of Cretaceous age.

The central plateau, or Serra do Espinhaço proper, shows along both flanks of the Diamantina section heavy beds of quartzitic sandstone, which dip sharply to the east on the eastern flank and to the west on the western (11, 12). Over the central part the dips are gentler and more variable, the beds in places being nearly horizontal. Over large areas the sandstone has been completely denuded away, revealing an underlying series of quartzites and argillaceous schists, with in one place a considerable patch of granite. As in the Paraguassú and Grão Mogol sections, there is here abundant evidence

[1] See Branner (18), who traced the coast Tertiary beds to the summit level of the Bahia and Minas Railroad in the Serra dos Aymores. The altitude is not given, as the railroad levelings were not obtainable, but by my aneroid readings it cannot be much over 200^{m}. Along the Bahia and São Francisco Railroad, as noted above, the Tertiary beds rise to 400^{m}, or a little more; but here the upper portion is of fresh-water origin, and perhaps much later than the lower beds, which correspond better in character with those along the Bahia and Minas line. In the basins of the upper Rio Doce in Minas Geraes, Tieté and Parahyba in São Paulo there are high-lying fresh-water Tertiary basins, with fossils, that seem to correspond with the one above considered.

that the sandstone is the source of the diamonds that characterize the region. A number of the workings are in decomposed conglomeritic portions of the sandstone sheet, and at Grão Mogol diamonds have been found in the sound rock as well.

The southern section of the range, forming the head of the Rio Doce basin, being in a region of very abundant rainfall, is much more deeply eroded than those above described, and along the usual lines of travel, which are parallel to its trend or cross it in deep gaps, its tectonic features are not clearly apparent. The central zone is occupied by great ridges, or blocks, of quartzites, or quartzitic sandstone, rising to an elevation of 1,500 to 1,900^{m}, and which, being comparatively barren of gold and of difficult access, are almost completely unexplored. These seem to represent a great sheet like that of the Jequetinhonha and Paraguassú sections, which on the lower grounds has been completely swept away, or so denuded as to be difficultly recognizable, especially as a very similar rock occurs as a member of the underlying formation. The latter consists of a great series of essentially argillaceous and micaceous schists, with intercallations of flaggy micaceous quartzites, ferruginous quartzites (itabirites), and limestones, which is frequently gold-bearing. In the bottom of some of the valleys gneiss, micaschist, and granite appear, and these are the predominant rocks in the region to the eastward of the serra, which is, however, so imperfectly known that the eastern margin of the Serra do Espinhaço zone cannot be satisfactorily traced. The western margin, as in the Jequetinhanha section, is abrupt and overlooks a similar region of truncated sedimentary rocks, which, however, throughout a considerable part of the section is separated from the base of the serra by a zone of granite and gneiss.

From the above sketch it appears that the Serra do Espinhaço consists of a basement complex of metamorphic and eruptive rocks overlain unconformably by one or more series of sandstone strata that have been disturbed by a system of northward-trending folds, whereas in the mountainous region of southeastern Brazil, of which it is an offset, the dominant trend is northeastward. In the southern sections (Jequetinhonha and Doce) the orographic movement producing the folds has also produced a certain amount of metamorphism in the form of shearing and granulation, accompanied by the develop-

ment of mica, giving the rock an appearance so similar to that of the quartzite members of the underlying metamorphic series that the two have been very generally confounded under the name of "itacolumite." In these sections, however, outcrops occur, as in the neighborhood of Diamantina, in which the rock is a typical unmetamorphosed sandstone or conglomerate; and it is now clear that metamorphism, when it exists, is a local, not a general, characteristic.

Regarding the age of the Espinhaço uplift, and of the beds affected by it, no satisfactory evidence is at hand, as thus far no fossils have been found in these beds, or in others whose relations to them have been clearly established. Up to the present all writers who have treated of the region, myself included, have considered it to be very ancient, Archean or early Palæozoic. This opinion was based largely on the metamorphism of the rocks in the Diamantina and Ouro Preto districts, and, in my own case, partly on the fact that in other parts of Brazil the epoch of folding and metamorphism on a large scale could be proven by fossil evidence to be pre-Devonian. Both of these arguments are evidently weak, and must now be put aside in view of the unmetamorphosed and comparatively modern aspect of the folded rocks of the Bahia section of the Serra do Espinhaço, and of the possibility of local disturbances affecting rock of Devonian or later age. In the coast regions of the states of Bahia, Sergipe, and Alagoas there are evidences of such disturbances which have some bearing on the question here considered.

On the lower Rio Pardo, Hartt (6) found a series of inclined conglomerates, sandstones, and shales, with obscure plant remains which he referred to the Devonian, and noted indications of the presence of the same series on the lower Jequetinhonha as well. In a recent excursion in this region I found that this series occupies a zone several kilometers wide, and was informed that to the westward there is a considerable zone of limestone (marble). Owing to the high state of the river, I missed seeing the fossil locality. The conglomerate also occurs at Salobro, about a league distant from the margin of the Rio Pardo, and here it is diamond-bearing (the so-called Cannavieiras diamond district), presenting considerable resemblance to the diamantiferous conglomerate of the upper Paraguassú region. The occurrence of this series on the Jequetinhonha was confirmed

by Dr. Joaquim Bahiana, a competent geological observer, and it evidently occupies a considerable belt along the eastern margin of the gneiss plateau. Branner (17) has described a similar fringe of presumably Palæozoic strata in the states of Sergipe and Alagoas, and I have seen traces of it to the northward of the city of Bahia in the neighborhood of Inhambupe. The fossils reported by Hartt were fragmentary and unsatisfactory, and his reference of them to the Devonian can only be considered as provisional. It is highly probable, however, that the series is Palæozoic, and certainly not older than the Devonian. On the other hand, the uplifted strata (consisting of conglomerates, sandstones, shales, and limestones) of Sergipe and Alagoas are certainly pre-Cretaceous.

The limestones of the upper São Francisco basin appear to represent, as Eschwege (2) has already indicated, two distinct geological formations which have not yet been discriminated. A part of them is certainly included in a disturbed series of sandstones and shales which is almost certain early Palæozoic and presumably older than the Espinhaço uplift; another part lies horizontally, at least in places, and is presumably newer. At Bom Jesus da Lapa, on the right bank of the São Francisco and almost due west from Rio de Contas, I found, in 1880 (8, 9, 10), badly preserved fossil corals of the genera *Favosites* and *Chaetetes* (?), which indicate middle or upper Palæozoic age (Upper Silurian to Permian). Possibly this limestone can be correlated with that above described to the east of the serra, but nothing definite can be said on this head. If, as above suggested as possible, the sandstone of the Jacobina region proves to be folded and of Cretaceous age, the question of the age of the uplift would be decided as Cretaceous or post-Cretaceous; but it hardly seems probable that this will prove to be the case.

The rocks entering into the composition of the Serra do Espinhaço fall naturally into three groups, each of which will probably eventually have to be subdivided into two or more. These are: (1) the gneisses and micaschists; (2) the schists, quartzites, and limestones of the auriferous regions; and (3) the quartzites and sandstones of the diamantiferous regions. With these are associated granites and other eruptives which apparently have not penetrated into the upper series and presumably antedate it.

As Eschwege has already remarked, gneiss and micaschist only appear in the lower levels of the Serra do Espinhaço zone, while, with their associated eruptives, they form the main mass of the mountains to the eastward and southward belonging to the Serra do Mar and Serra da Mantiqueira systems. These rocks have been but little studied in the region here discussed, but, so far as known, they correspond with those of the other parts of Brazil, and can safely be considered as of Archean age. It also seems tolerably safe to consider the great majority of the Brazilian gneisses (at least those that from their resistance to decay are most in evidence) as sheared eruptives, the original types being granites, norites, diorites, etc. A part of the micaschists are also of eruptive origin, but presumably the larger part will prove to be metamorphosed sedimentaries. In the part of Brazil here considered these rocks form a great shield-shaped area in eastern Minas Geraes and Bahia (with the adjacent states of Espirito Santo and Rio de Janeiro), which for the most part has been dry land since Archean times. About its borders, particularly on the west, and over its lower-lying portions the later sedimentary deposits have been laid down.

The schistose series of the Serra do Espinhaço and adjacent regions, which may conveniently be denominated the *Minas series*, consists of a great complex of predominantly argillaceous schists, with subordinate masses of ordinary quartzites, ferruginous quartzites (itabirites passing to pure iron ores), and limestones. All of these rocks are greatly sheared, and characterized by a greater or less development of a mica-like mineral (biotite, sericite, micaceous hemetite, chlorite, talc, etc.); and as in general they are much decomposed, there is great difficulty in distinguishing the different members (except the quartzose and ferruginous ones), and thus far no successful attempt to work out the order of succession in them has been made. It is tolerably certain that the quartzose, ferruginose, and calcareous members are repeated at various horizons, and eventually they will serve as reference lines for establishing the subdivisions of the series; but before this can be done the repetition due to folding and faulting must be determined and taken into account. Apparently the whole series has been bent into closely appressed overturned folds, and doubtless it has been much faulted. Until

the region, or at least a typical portion of it, has been accurately mapped, any attempt to determine its detailed structure is hopeless.

The argillaceous members of the Minas series include micaceous (mainly, if not exclusively, sericitic) schists, calc schists, graphitic schists, chloritic schists, and talc schists. A considerable part, if not the whole, of the last two types consists of undoubtedly sheared and metamorphosed eruptives, and I have elsewhere attempted to show (13, 14) that a part of the sericitic schists are of the same origin.[1] There can be no doubt, however, that the greater part of the series is of sedimentary origin. Its age can only be guessed at, but it seems tolerably certain that it cannot be younger than Cambrian, and that it may be older.

The Minas series has always been regarded as the characteristic formation of the Serra do Espinhaço, and it is certain that it, or another series very like it, appears throughout the entire length of the range. To the northward of the Rio Doce section the characteristic ferruginous and calcareous members seem to disappear in the zone of the serra, though they occur again on the banks of the São Francisco between Urubú and Joazeiro. It seems probable, therefore, that more than one geological series is here included. It is also certain that these characteristic members occur on both sides of the Rio Doce section at considerable distances from the reputed margins of the Serra do Espinhaço zone, and with indications of folds with a northeasterly trend, and thus parallel with the neighboring Archean ranges. It seems probable, therefore, that their first and strongest folding was due to a movement producing northeast-trending folds, and presumably involving the shale, sandstone, and limestone series of the São Francisco basin as well. The occurrence farther southward in the Paraná basin of a series very similar to this last, and which has been involved in the northeast folds of the adjacent Archean region, confirms this point of view. These rocks of the Paraná basin, like those of the São Francisco, are in general but slightly metamorphosed and are overlain, in the state of Paraná, by horizontal strata containing Devonian fossils (15). Though they

[1] Since the above-cited papers were written, a specimen has come to hand showing one of the types there discussed (the monazite-bearing schist of Sao João da Chapada), with a well-defined eruptive contact with quartzite.

have afforded no fossils, they are presumed to be of Cambrian or Silurian age.

This sedimentary series of the Paraná basin is abundantly injected with granite, which, for this region at least, fixes the age of the granitic eruptions as pre-Devonian. The granites are of various types (hornblendic, biotitic, and muscovitic), and doubtless several periods of eruption are represented among them, but presumably these were contemporaneous with, or posterior to, the orogenetic movements that produced the folding. The granites that occur quite abundantly in the areas occupied by the Minas series have not been studied, but it may be presumed that the above conclusions regarding age and periods of eruption will apply to them as well. Aside from the granites, these areas present frequent outcrops of basic eruptives of gabbroitic, diabasic, and peridotitic types, which, so far as observed, show signs of metamorphism (a certain amount of shearing and an uralitic alteration of the pyroxene), which may plausibly be attributed to the later movement of upheaval that involved the overlying sandstone as well. So far as observed, this last has not been affected by eruptive injections, nor do the auriferous veins so characteristic of the Minas series extend into it.

The sandstone capping of the Serra do Espinhaço zone presents, everywhere that it has been examined, great uniformity of aspect, except that the division into two series noted in the Paraguassú section has not been observed elsewhere. The conglomeritic character of the upper beds of this section is general throughout the range, and although in the Jequetinhonha and Doce sections the rock is in places somewhat metamorphosed, this apparently is not a sufficient reason for considering it as distinct. Another very general characteristic is the occurrence of diamonds, but these appear to be lacking, at least in workable quantities, in the extreme southern portion of the range in the vicinity of Ouro Preto, and also in the northern portion in the Jacobina region and beyond.[1] As already stated, there are reasons for suspecting that the Jacobina sandstone is more recent than that of the more southern portions of the range, but on this head nothing definite can be said. As to whether, with this

[1] The question of the mode of occurrence of the diamond in this range and other parts of Brazil will be discussed elsewhere.

exception and that of the lower beds of the Paraguassú region, the sandstones of the range are to be considered as constituting a geological unit, or not, must also remain in doubt, though I am personally inclined to an affirmative opinion.

The geological age of the characteristic rocks of the Serra do Espinhaço zone, and of the orogenetic movement that has given them their present attitude, must also remain in doubt. The most that can be said is that neither is as ancient as has hitherto been supposed, and apparently the Devonian can be taken as the extreme limit of age. This, however, includes the hypothesis, not in itself improbable, of a localization of the orogenetic movement, since the definitely known Devonian deposits of other parts of Brazil (in the states of Paraná, Matto Grosso, and Pará) were not affected by it. The other extreme age limit is the Cretaceous, but until the Jacobina section is examined, and the reputed find of fossils verified or disproved, this hypothesis can neither be accepted nor completely put aside. The hypothesis of a Mesozoic age (Cretaceous or pre-Cretaceous) is a seductive one, as this would bring into line, at least as regards age, the occurrences of the diamond in various parts of Brazil and in South Africa (17); but against this we have the assumed, though not definitely proven, relation of the horizontal limestones of the São Francisco valley and of the Rio Una, which, for the present at least, must be regarded as Palæozoic and newer than the Espinhaço uplift. All things considered, it seems to me most probable that the age, both of the rocks and of the uplift, will eventually prove to be the middle or late Palæozoic (Devonian to Permian).

The escarped margins of the Serra do Espinhaço zone is in many places very suggestive of faulting, and I was until recently inclined to admit the existence of fault lines of gigantic proportions. With a better knowledge of the adjacent regions, it seems probable that this feature may be due in great part to denudation under conditions of drainage and elevation different from the present ones. The range throughout a considerable portion of its length is bordered by well-defined denudation plains, some of which, as that of Joazeiro, are but slightly sculptured, while others are dissected by valleys excavated from 200 to 300^{m} below the general level. In the region of the middle Jequetinhonha the conditions at one time, probably

during a part of the Tertiary age, were such that an inland basin was filled up with horizontal deposits nearly to the level of the surrounding denudation plain, and later, through a rise in the land, both were dissected to a depth of 200 to 300^{m}. About the same amount of elevation is indicated by the coast Tertiary beds, by the Cretaceous strata near the Paulo Affonso cataract, and by the dissection of the denudation plain and horizontal Cretaceous (?) strata of the upper São Francisco basin; so that this movement may be taken to have been general and of approximately equal amount throughout the whole region. The Cretaceous strata of the Paulo Affonso region seems to have been laid down on a still older denudation plain, which must have stood at about the level of the sea, since the fauna contains a mixture of fresh-water and marine forms (cyprids and sharks). The denudation of the mountain zone was therefore effected by successive stages, and under different conditions of drainage and elevation; and to this circumstance are doubtless due many of its topographic characteristics.

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THE VARIATIONS OF GLACIERS. XI[1]

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The following is a summary of the *Tenth Annual Report* of the International Committee on Glaciers.[2]

REPORT ON GLACIERS FOR 1904

Swiss Alps.—Of the ninety glaciers under observation in Switzerland, seventy-three were measured in 1904. Five are uncertain, and the others are retreating or are stationary; none are surely advancing. We therefore see that there is a still greater tendency to retreat this year than last. The temperature in 1904 was markedly above the normal, and this undoubtedly had some influence on the retreat of the glaciers.[3]

Eastern Alps.—The tendency to retreat is nearly everywhere noted. Of fifty-one glaciers observed, forty-four are retreating and only four actually advancing. Here also we find an increased tendency of the glaciers to recede. In the Ortler group the Duldenferner has advanced 11 meters since last year, but the others have been retreating at the rate of from 3 to 10 meters a year. The Fürkeleferner has been retreating much faster, namely, 31.7 meters per year since 1899. In the Oetztal the retreat is also general at the rate of from 10 to 20 meters per year. The Mittelbergferner has retreated 119 meters since last year; the year before that its retreat was 83 meters. The Mitterkarferner has advanced 3.3 meters per year since 1901. The Vernagtferner is about stationary, but its rate of motion has diminished, and a retreat will probably be reported soon. The velocity of the Guslarferner has also diminished. On the other hand, the motion of the Hintereisferner has slightly increased, but the end has retreated 20.6 meters since last year. All the glaciers of the Stubaï group are retreating from

[1] The earlier reports appeared in the *Journal of Geology*, Vols. III–XIII.

[2] *Archives des sciences physiques et naturelles* (Geneva, 1905), Vol. XX, pp. 62–74, 169–90.

[3] Report of Professor Forel and M. Muret.

3 to 10 meters per year. The Gliederferner, in the Zillertal, has advanced 34 meters since 1899 and has formed a moraine in front; its motion is a third less than it was from 1897 to 1899, during which time it advanced 36 meters; the very end is still swollen, but the rest of the glacier is thinner than normal. The other glaciers of this group are retreating or are stationary. The glaciers of the Venediger group are all retreating at rates varying from 0 to 22 meters per year. The Grosselendkees in the Ankogel group has advanced 1.4 meters since 1903. The other glaciers of this group and those of the Glockner are retreating.[1]

Italian Alps.—The snow-fields of the Cavallo, which were reported as having increased considerably in 1903, were found in 1904 to have diminished very much. The glaciers on the south side of Monte Rosa seem to be advancing, but they have not yet reached their limits of 1901. In the Graian Alps there is evidence of a considerable diminution of the glaciers. The glaciers on the south side of Mont Blanc are in general retreating, and in some cases markedly. The glacier des Jorasses, which has been retreating, shows evidence of an approaching advance. The general result regarding the Italian glaciers of Mont Blanc is that the phase of retreat is about finished, and that the thickening which began in the upper reservoirs is now approaching the ends and about to cause an advance. The snowfall in the higher regions has been very heavy.[2]

French Alps.—A careful study of the glacier Noir and the glacier Blanc has been made and maps prepared on the scale of 1/10,000.[3] These two glaciers, which are very near together have shown striking differences in their behavior. The glacier Noir has been retreating steadily since 1860; and the glacier Blanc, on the other hand, retreated from 1865 to 1886, but advanced between 1889 and 1896; since then it has been retreating. It occupies a very high reservoir, 3,000 to 3,300 meters in altitude, and has a very clean surface. The increased precipitation which occurred toward the end of the nineteenth century caused it to advance. The glacier Noir, on the other hand, lies, for its

[1] Report of Dr. H. Angerer.

[2] Report of Dr. F. Porro.

[3] Charles Jacob and George Flusin, "Étude sur le Glacier Noir et le Glacier Blanc," *Annuaire de la Société des Touristes du Dauphiné*, 1905.

greater part, in a deep valley, and has been much affected by the warm weather, and has consequently retreated.

Professor Kilian[1] has published a short account of the glaciers of the Dauphiné, in which he concludes that there is a general tendency toward the diminution of these glaciers, and he thinks that a number of them will disappear before long; some of the smaller ones have already disappeared.

All the glaciers of Savoy which have been observed are retreating, and some of the small ones have disappeared. The same statement applies to the glaciers of the Pyrenees, with the exception of one, the Pai Bache, which has increased since 1883, but seems now to be retreating.[2]

Norway.—In the Jotunheim region twenty glaciers were found to be retreating and four advancing. In the Jostedal four are retreating and two advancing; whereas in the Folgenfon the three glaciers observed were all advancing. There seems to have been considerable difference in the snowfall in the different regions, but it does not seem to correspond to the changes in the glaciers.[3]

Sweden.—The Mika glacier was found to have advanced from 7 to 10 meters between 1902 and 1904.

Greenland.—The glacier of Jakobshavn has undergone many changes in its water front; sometimes a portion of the front has advanced, and then again, as a result of the calving of the ice, it has been cut back; but, on the whole, since 1902 the central parts of the end retreated nearly 400 meters, and the sides about 210 meters. The glacier has also diminished in thickness about 16 meters near the side. Other small glaciers show a slight retreat.[4]

Russia.—A large number of glaciers have been visited in the Caucasus, and they all seem to be retreating; but some of them show a swelling in their middle courses, which may cause an advance before long. In the Pamir there are many small glaciers, some of which have been advancing in the last few years.[5]

[1] *Les Glaciers du Dauphiné* (Grenobl., 1904).

[2] Report of M. W. Kilian.

[3] Report of M. P. A. Oyen.

[4] Report of M. K. J. V. Steenstrup.

[5] Report of Colonel J. de Schokalsky.

South America.—Dr. Benrath has collected some observations of the glaciers in the Coast Cordillera of Peru, which show that they have been retreating for the last twenty-five years; and the bare condition of the ground in front of the ice shows that this retreat has existed for a still longer period. The existence of extensive moraines at some distance from the glaciers indicate a former glacial period in this region (12° south latitude).

Captain Cresthwait states that most of the larger glaciers seen by him during a trip through the straits of the southern end of Patagonia showed signs of shrinkage.

Africa.—The crater of Kibo, Mount Kilimandjaro, was visited by Dr. Uhlig in 1901 and 1904. In the former year the crater contained more snow and ice than at the time of Dr. Meyer's visit in 1898, but the snow did not extend to as low a level on the slopes of the mountain; and this was after a very dry season. In 1904, on the contrary, after a season of unusually heavy precipitation, there was less snow and ice in the crater of Kibo than has been reported at any earlier period.

Canada.—A very interesting account of the glaciers of Canada has been given by Miss Ogilvie.[1] She divides them into three groups: First, those of the central and eastern Rockies which, in general, lie in very deep valleys surrounded by nearly vertical cliffs, and are fed by avalanches from the slopes, or from the hanging glaciers above; that is, they are débris glaciers. Their whole course is practically below the snow-line, and they are covered very completely with rubbish, so that for a large part of their surface the ice is entirely invisible. Of this group the Victoria glacier has retreated but little. The glacier of the Ten Peaks valley is advancing. The glacier of the Consolation valley was but slightly shorter than at the time of its recent maximum extension, and the other glaciers of this group are probably in the same general condition. The second group of glaciers, which lie in the western Rockies and Selkirks, are practically like the ordinary valley glaciers of Switzerland, except that they are, as a rule, broader and shorter. The moraines are practically similar to the moraines of the Swiss glaciers. Of this group the Wapta shows a recent rapid retreat. The Illecillewaet, the Asulkan, the Geikie, and the Deville glaciers are all

[1] The Effect of Super-glacial Débris on the Advance and Retreat of Some Canadian Glaciers," *Journal of Geology*, Vol. XII (1904), pp. 722–43.

in rapid retreat. Of a third class of glaciers, intermediate between the other two, one is advancing and the other retreating.

Messrs. Vaux have continued their observations of some of the Canadian glaciers as follows:

There is evidence of a continued retreat of the Victoria glacier, at about the rate of previous years. The Illecillewaet continues to recede, the tongue being 5 feet behind the location of last year. This recession is much less than that noted for several years past. The glacier continues to decrease in thickness and width. The slight advance of the Asulkan glacier, noted the last three years, appears to have ceased, and in 1904 the tongue was 11 feet below the range line of 1899, showing a recession of 5 feet since 1903. Changes in the form of the glacier appear slight. The Yoho glacier is evidently retreating and decreasing in thickness. It was last visited in 1901; since that date the tongue has receded 89 feet, or on an average of $29\frac{2}{3}$ feet per year. A very splendid ice-arch on the right side of the glacier was one of the notable features last summer.

REPORT OF THE GLACIERS OF THE UNITED STATES FOR 1905.[1]

Professor U. S. Grant has visited the glaciers of Prince William Sound, Alaska, and reports various changes in them. The Shoup glacier lies in the neighborhood of Valdez; two large rocks are being exposed by the retreat of the glacier which were not visible four years ago; along the sides there is a broad space of bare ground free of soil and vegetation, and the whole aspect of the glacier indicates that it is retreating. Photographs were obtained from fixed points which will be useful in determining future changes. The western part of Columbia glacier—i. e., the part west of Heather Island—is rapidly discharging, and presents apparently the same appearance as when visited by the Harriman Expedition. At the north end of the small island north of Heather Island, on which the front of the glacier is resting, and where a few years ago the glacier had intruded and overturned the front of a forest, a photograph was obtained from the same position as one taken by Mr. Gilbert in 1899. At this point the front of the ice has retreated 160 feet since 1899. On the ground since vacated by the

[1] A synopsis of this report will appear in the *Eleventh Annual Report* of the International Committee. A report of the glaciers of the United States for 1904 was given in this *Journal*, Vol. XIII, pp. 316–18.

glacier, there is very little vegetation—practically nothing except fireweed, which has encroached upon this territory only a few feet. Brooks glacier enters the head of Unakwik Bay. It is formed by the junction of two branches, and comes down to tide water; the front is about a mile and a quarter in width and is actively discharging. As viewed from a distance of about a mile, trees and bushes are seen to come down to the ice, and there is no zone, or a very narrow one, between the ice and the vegetation. The extreme front of Barry glacier, Port Wells, has retreated at least a mile since 1899. The long point which projected into Doran Strait for nearly two miles has entirely disappeared, and the front is now nearly straight across. The little tongue of ice which lay along the east side of the glacier has also disappeared. Photographs and sketches of the front of the glacier were obtained to show its exact position in 1905.

Photographs and observations were made of a number of the smaller glaciers and all seem to be in retreat. Several of these have been observed for the first time, and the data obtained will serve as a basis for future changes.

A short account of the glaciers of the Wrangell Mountians, with a map showing their locations, is contained in Mr. W. E. Mendenhall's "Geology of the Central Copper River Region," Alaska.[1] Some of the glaciers are 30 and 40 miles long. Those of the west slope are smaller than those flowing in other directions, which is ascribed to the volcanic heat of the rocks. The glaciers were at one time much larger than they are now, but no information is given regarding recent changes.

The Yakutat Bay glaciers were especially studied last summer by Professor Tarr and Mr. Martin,[2] and the positions of the glaciers compared with their positions as noted by Professor Russell in 1891, and by the Harriman expedition in 1899. The Turner glacier, which reaches the sea in Disenchantment Bay, indicated a general recession between 1891 and 1899, and a slight advance on the sides between 1895 and 1905 with a recession in the center. The northwestern half of Hubbard glacier has also advanced in the last six

[1] U. S. Geological Survey, *Professional Paper No. 41*.

[2] "Glaciers and Glaciation of Yakutat Bay," *Bulletin of the American Geological Society*, Vol. XXXVIII, pp. 145–67.

years, though the amount could not be determined; there is no definite evidence of advance in the southern side of the glacier. One of the Indians who accompanied the expedition was confident that the Hubbard had been advancing for the last ten or twelve years, but this idea does not seem to be well supported by the maps. The Nunatak glacier ends in tide-water with a short arm resting on the land, separated from the main stream by a rocky knoll, which was completely surrounded by the ice when visited by Professor Russell in 1891. Comparison of Mr. Gilbert's photograph of 1889 with one taken in 1905 shows that the tide-water front has retreated almost a mile. The arm resting on the land has also shortened from 200 to 400 yards, so that the knoll is now not more than half surrounded by the ice. The Hidden glacier ends some distance from tide-water on a gravel deposit which in places is underlain with ice. The photographs show that this glacier has retreated about one-quarter of a mile. The Cascading glacier near the Nunatak is retreating, as are also many other small glaciers which were examined by Messrs. Tarr and Martin. One remarkable glacier on the west side of Disenchantment Bay, whose end is about 1,000 feet above the water, slid out of its bed and was precipitated into the bay on July 4, the day after it had been photographed. The glacial gravels in this region were especially studied, and the late glacial history there corresponds very closely with that made out for Glacier Bay. The great earthquake of September, 1889, which appears to have been central in the neighborhood of Yakutat Bay, and which made a number of faults in that region, has not left any marked changes in the glaciers such as have been observed in Glacier Bay. It is possible that the breaks caused by the earthquake have been made up since.

Not very much information has been received regarding Muir glacier, but no changes have apparently taken place. The same report is made regarding the Taku glacier, which apparently is not undergoing any special changes; but photographs taken in 1905 reveal a marked advance over the position of the glacier in 1890, as shown by a sketch made that year. Davidson glacier is apparently retreating, but no measures have been made (Davidson). A noticeable recession has taken place in the hanging glaciers in the Chilcat

River Valley between 1898 and 1905, although no measures have been made. The summer of 1905 was unusually warm, and the glacier streams were very much larger than usual (Flemer).

Last summer the Mazama Club of Portland, Oregon made its annual excursion to Mount Rainier. General Howard Stevens, who, with Mr. P. V. Van Trump, made the first ascent of Mount Rainier in 1870, was one of the party. He recognized some marked changes since his former visit. The Paradise glacier has retreated about 800 feet. The snow in the western crater on the summit was at least 40 feet lower than in 1870, and the wind-swept ridge separating the two craters, which was bare in 1870, was covered by a mound of snow 30 feet high in 1905. Mr. Longmire, who has been living near Mount Rainier for the last twenty-five years, thinks the Nisqually glacier has retreated a quarter of a mile in that period (*Mazama Magazine*). Professor J. N. LeConte made some measures of the movement of this glacier, and found a velocity of 22.4 inches per day at a distance of 3,000 feet from the end. He also erected a monument near the end as a station for the determination of future changes.[1] The precipitation in Oregon has been below normal for some years. The record at Portland shows a mean annual precipitation of 46.83 inches; whereas the average for the last six years has only been 35.47 inches. It is not surprising, therefore, that the glaciers observed on the southern side of Mount Hood are retreating; the White glacier is retreating less rapidly than the Zig Zag and the small one to the west (Montgomery). There is no new information regarding the recent variations of the Mount Adams glaciers, but a comparison of photographs taken in 1895 and 1901 shows that the ice at the end of Avalanche glacier, on the west side of the mountain, diminished in thickness at least 25 feet in that interval.

The Sperry and Harrison glaciers, and a small unnamed one on Mount Jackson, Montana, give evidence of a very recent retreat by the terminal moraines which they have deposited a short distance from their present ends, and which are so recent that vegetation has not yet taken hold upon them. (Chaney.)

Judge Henderson measured the movement of the Arapahoe

[1] His complete article will be published in the new *Zeitschrift für Gletcherkunde* and in the Sierra Club *Bulletin*.

glacier, Colorado, and found a velocity of 27.7 feet from August 30, 1904, to the same day one year later. The glacier continues to shrink along the sides, but has not retreated in the center. The snow-line, which was quite low in 1903 and 1904, has receded nearly to the bergschrund, a change which is not explained by the records in the nearest Weather Bureau stations.[1]

Hallet glacier seems to be a trifle larger than it was a year ago. The snow seems more abundant, showing a curious difference from the Arapahoe glacier near by. (Mills.)

[1] "Arapahoe Glacier in 1905," *Journal of Geology*, Vol. XIII (1905), p. 156.

CORRELATION OF THE RAISED BEACHES ON THE WEST SIDE OF LAKE MICHIGAN[1]

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INTRODUCTION

The eastern border of Wisconsin, along the western shore of Lake Michigan and around Green Bay, has long been known to bear the marks of a series of stages of the extinct glacial Great Lakes. Terraces, bluffs, and beach ridges at various altitudes above the present lake were briefly described in 1877 by Dr. T. C. Chamberlin, in his report on the *Geology of Wisconsin.*[2] In the summer of 1893 Mr. F. B. Taylor touched at several points on the Wisconsin shore, in a rapid reconnaissance around the Great Lakes.[3] The highest shore-line discovered by him at Kewaunee, Green Bay, Sturgeon Bay, and northward through the Upper Peninsula of Michigan was found to rise toward the north at a rate of more than a foot per mile, as if due to regional deformation of the extinct water-plane. The Door County peninsula (north of Sturgeon Bay) was not visited; but the early measurements of Chamberlin in a general way confirmed this view. The "highest shore-line" was later identified by Taylor as the beach

[1] Published with the permisssion of the Director of the Wisconsin Geological and Natural History Survey.

[2] *Geology of Wisconsin*, Survey of 1873–77, Vol. II, pp. 219–28.

[3] "A Reconnaissance of the Ancient Shore Lines of Green Bay," *American Geologist*, Vol. XIII (1894), pp. 315–27; and other papers published in the *American Geologist* the same year.

of Lake Algonquin—a great lake which occupied the Huron, the Michigan, and part of the Superior basins, while the ice formed a dam across low passes to the northeast. In the absence of direct observation south of Kewaunee, the plane of this Algonquin beach was extended by inference so as to pass under the present lake near Two

FIG. 1.—Map of part of the Great Lake region.

Rivers. Still later observations by Taylor and others, however, pointed to the probability that the shore-lines become horizontal above Lake Huron and Lake Michigan, encircling the southern ends of both.

In the southeastern part of the state and further south, around the head of Lake Michigan, a series of beaches, studied in detail by Mr. Frank Leverett, Dr. W. C. Alden, and others on the United States

Geological Survey,[1] were taken to mark a local ice-front lake, Lake Chicago. Of these beaches, the highest, about 60 feet above the lake, and a lower one about 40 feet, were not known to extend north of Racine County, Wisconsin, until very recently, when Alden found a terrace near Belgium (a few miles north of Port Washington) which corresponds somewhat closely to the 40-foot plane.

According to Taylor's studies, these beaches seemed to lie wholly above the plane of Lake Algonquin. Lower beaches of Lake Chicago, forming a complex group from 10 to 25 feet above Lake Michigan and called the "Toleston" beaches, had not been traced northward beyond Belgium when the present study was undertaken; and the actual relation between these and the inferred Algonquin plane was doubtful. It was suspected by Leverett, Chamberlin, and others that the lower beaches of the Toleston group (those from 10 to 15 feet above the lake) in the Chicago district might be shore-lines of Lake Algonquin.

In the summer of 1905 opportunity was given the writer by the Wisconsin Geological and Natural History Survey to study the old shore-lines of eastern Wisconsin with these problems of exploration and correlation in mind. Sufficient evidence was collected, it is thought, to show that only the beaches above 40 feet in the Chicago-Sheboygan district belong to a separate Lake Chicago; that the 20–25-foot Toleston beach of the Chicago district is the shore-line of Lake Algonquin; and that the strong 14-foot terraces and ridges of southeastern Wisconsin and northeastern Illinois mark the border of a later stage of importance, known as the stage of the Nipissing great lakes. It is the purpose of this paper to show on what grounds these conclusions were reached.

THE FIELD-WORK

The distance around the shores of Green Bay, from Marinette southward to Green Bay City, and thence northeastward to Washington and Rock Islands, is about 100 miles. From Washington Island southward along the shore of Lake Michigan to the Illinois line is approximately 200 miles. This entire stretch of shore, except

[1] See *Monograph XXXVIII*, U. S. Geological Survey, "The Illinois Glacial Lobe," by Leverett; and the Chicago Folio, No. 81, with discussion of Lake Chicago by Alden.

for about 20 miles near Milwaukee (part of the area recently covered by Alden), was traversed during the field season, chiefly on foot. Gasoline fishing-boats were used to advantage near the end of Door County Peninsula and on the southeastern shores of Green Bay. South of Sturgeon Bay the traverse was a continuous one, the present shore being followed wherever it has cut back a line of high cliffs beyond the earlier shore-lines, as is very common, and the fragments of abandoned shore-lines being followed from their beginnings, at the

FIG. 2.—Boyer Bluff, at the northwestern end of Washington Island. Three steps or notches in the headland mark three important stages of Lake Algonquin.

lake cliffs, to their endings further along. North of Sturgeon Bay on the less thickly settled peninsula, the beaches were not followed continuously, but were visited at short intervals of from one-half to five or six miles, wherever they are most accessible and best developed. Although the hand level was used in favorable places, to economize time, such measurements were not regarded as critical. With the spirit or "wye" level accurate profiles of the entire series of beaches were measured at about fifty localities, most of them on the Door County peninsula, where the best records were found. By this means it was possible to correlate the fragments with more than usual con-

fidence, and thus to reconstruct the water planes of the extinct lakes.

CHARACTER OF THE RECORD

On the rocky and exposed peninsula north of Sturgeon Bay the shore-lines are developed in conspicuous form. Fig. 2 shows a characteristic headland cut by the waves at successive levels so as to look like a great flight of steps. Heavy beach ridges of cobble stones occur across the bay heads or on shelving shores (see Fig. 3). The record of

FIG. 3.—Beach ridge of the Nipissing shore-line at Graceport, near Sturgeon Bay. It stands 19 feet above the level of Lake Michigan. On the left, between this beach and the shore of Green Bay, are lower ridges.

successive stages is singularly complete in this district, because exposure was great enough to allow each successive water-plane to be registered, while the rocky surface was usually too resistant to allow the shore cliffs of a lower lake stage to be cut back beyond higher shore-lines, and thus to destroy them.

South of Sturgeon Bay the expression of the beaches undergoes a marked change, corresponding to the change in the character of the ground. In place of bed-rock at the surface, there are thick red-clay deposits, in part ice-laid and in part water-laid, into which the waves

can cut with ease. Consequently the present shore south of Algoma commonly consists of high red-clay cliffs, which are rapidly retreating under the attack of the waves, and have long since eaten away the abandoned shore-lines of higher stages. When fragments are preserved, moreover, they commonly show that the lake at the Nipissing plane (the next important one above the plane of the present lake) cut back beyond the earlier shore-lines of Lake Algonquin and Lake Chicago. The record south of Sturgeon Bay, then, is relatively

FIG. 4.—Terrace and bluff of Lake Algonquin near Sturgeon Bay, 40 feet above Lake Michigan.

incomplete, and fragments of the lower stages are more common than those of the higher.

The same is true of the southeastern border of Green Bay. Along the low western shore of Green Bay, on the other hand, deposition of beach ridges has been the rule from the first, so that no cliff recession at the lower stages has here destroyed the record of earlier stages. There is an almost complete series of sandy ridges. But the weakness of expression of these beaches, probably in large measure an original weakness, together with the sandy structure which has per-

mitted the wind to spread and otherwise modify them, makes it somewhat difficult to find enough data for accurate measurements. Nevertheless, enough was found to show that the shore-lines on both sides of Green Bay correspond exactly to those on the Lake Michigan border.

THE ALGONQUIN SHORE-LINES

The systematic variation in altitude of the highest shore-line of Lake Algonquin can be seen by reference to the map. Here the figures mark the altitude of the Algonquin beach or terrace at each locality where it was measured with the spirit level. It is found by experimentation that these points lie closely in harmony with a tilted (or more accurately a warped) plane, on which the direction of steepest ascent is about N. 15° E., and that of no differential uplift is about N. 75° W. On Washington Island the highest Algonquin beach is about 90 feet above Lake Michigan. When followed southward, it is found to decline rather steadily until it is only 40 feet above the lake at Sturgeon Bay (Fig. 4). Throughout this distance it is marked either by a strongly cut terrace or by a well-built ridge of gravel or chip stone. Above it there are no signs of submergence. Below it several other shore-lines can be traced with equal distinctness. They have similar warped attitudes, and represent successive later planes of the lake, determined by repeated uplifts in its northern part.

In Fig. 5 the warped planes are drawn in profile in the direction of steepest inclination, N. 15° E. Each ordinate records a spirit-level measurement of the crest of a beach ridge or the base of a cut bluff, according to symbols which are explained in the legend. The vertical scale is 500 times the horizontal, greatly exaggerating the slope of the planes, and proportionately magnifying the discordance of the ordinates. In view of this, and of the chance of discordance due to (*a*) original variation in crest-line of the beaches and terraces, (*b*) the error involved in determining the datum lake-level during days when waves were running high, and (*c*) the error in leveling, which probably amounts to a fraction of a foot, the accordance of ordinates to the inferred planes of the highest Algonquin beach is remarkable. Nearly all the ordinates lie within 3 feet of the plane; and the few which are 5 or 6 feet too high are all of them points which were regarded at the time of their discovery as ridges built up to exceptional height

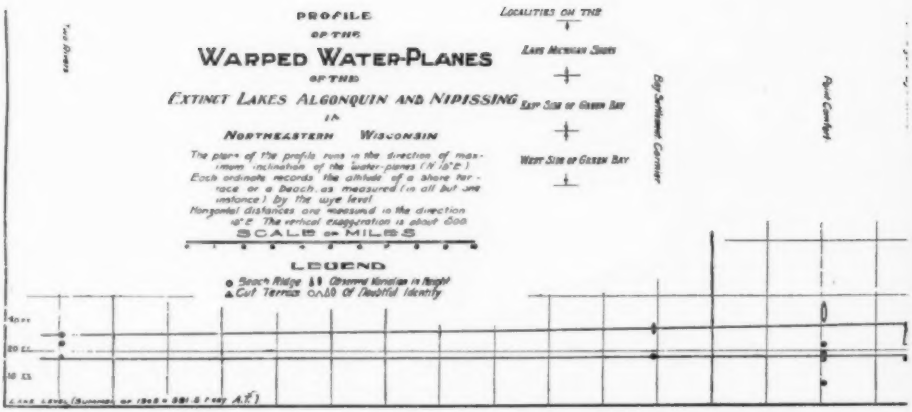
by storm-waves in places of unusual exposure. A great barrier ridge at Egg Harbor, for instance, which was built in 60 feet of water across the head of a bay, has a crest 7 feet higher than the cut terrace from which it tails out. The terrace corresponds closely to the inferred Algonquin plane; and a distant beach ridge lies at the same level just below the top of the barrier embankment. The discordance of this ordinate, like the two or three others, is wholly within expectation.

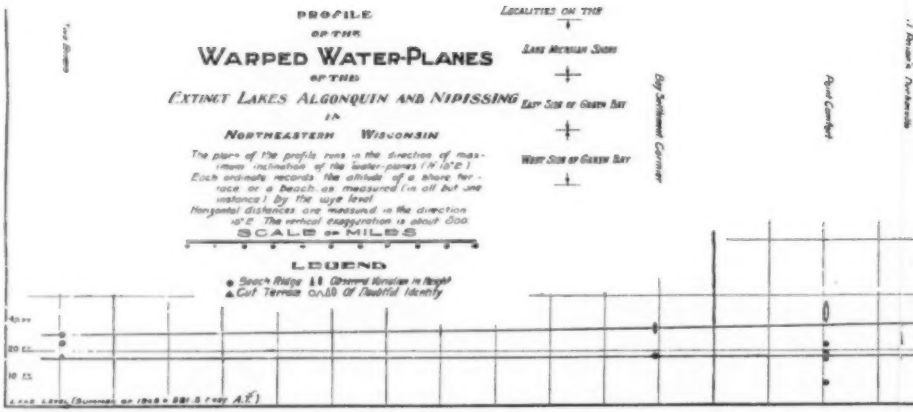
It is seen that this reconstructed plane slants southward from Washington Island at about 1½ feet per mile to Sturgeon Bay (slightly more in the northern part and less in the southern part), and that it suddenly becomes flatter near Sturgeon Bay and slants southward at the rate of about 8 inches per mile to Two Rivers, where it is nearly, if not quite, horizontal. For long distances south of Sturgeon Bay the Algonquin shore-line has been cut away during later stages; but the extinct flood-plains, now terraces, are found at appropriate heights in most of the stream valleys.

Two lower Algonquin planes, marked on Washington Island and near Death's Door by deeply cut terraces, can be traced southward in a similar way, converging slightly in that direction until at Sturgeon Bay they are so close together as to be difficult to identify separately. Ordinates which lie between the planes and mark weaker beaches suggest short-lived stages of intermediate age. In only one case (plane A′) has an attempt been made to reconstruct these less distinct planes.

THE NIPISSING AND LOWER SHORE-LINES

Below the slanting and diverging Algonquins is a nearly horizontal plane which is marked everywhere, and more strongly than any other (see Fig. 3). From 22 feet above the lake at Washington Island this declines almost imperceptibly to about 16–18 feet at Two Rivers—a drop of only 4 or 6 feet in a distance of about 90 miles. The remarkable strength of this shore-line—usually a high-cut bluff and broad terrace—together with its correspondence in altitude with the Nipissing shore-line traced by Taylor in the northern part of the Great Lake region down to Gladstone and Escanaba (just north of the eastern Wisconsin district), leaves little doubt that it marks the Nipissing plane, a stage of the lakes when both the North Bay outlet and


PROFILE
OF THE
WARPED WATER-PLANES
OF THE
EXTINCT LAKES ALGONQUIN AND NIPISSING
IN
NORTHEASTERN WISCONSIN
The plane of the profile runs in the direction of maximum inclination of the water-planes (N 10°E.)
Each ordinate records the altitude of a shore terrace or a beach, as measured (in all but one instance) by the wye level.
Horizontal distances are measured in the direction of E.
The vertical exaggeration is about 600
SCALE OF MILES
LEGEND
Localities on the
Lake Michigan Shore
East Side of Green Bay
West Side of Green Bay
Bay Settlement Corner
Point Comfort
Beach Ridge
Cut Terrace
Obscure Variation in Height
Of Doubtful Identity
400 ft.
200 ft.
100 ft.
Lake Level (Summer of 1905 = 581.5 feet A.T.)


PROFILE
OF THE
WARPED WATER-PLANES
OF THE
EXTINCT LAKES ALGONQUIN AND NIPISSING
IN
NORTHEASTERN WISCONSIN
The plane of the profile runs in the direction of maximum inclination of the water-planes (N 18°E.)
Each ordinate records the altitude of a shore terrace or a beach, as measured (in all but one instance) by the wye level.
Horizontal distances are measured in the direction 18°E. The vertical exaggeration is about 200.
SCALE OF MILES
LOCALITIES ON THE
LAKE MICHIGAN SHORE
EAST SIDE OF GREEN BAY
WEST SIDE OF GREEN BAY
Bay Settlement Corner
Point Comfort
LEGEND
Beach Ridge
Cut Terrace
Observed Variation in Height
Data Of Doubtful Identity
400 FT.
200 FT.
100 FT.
LAKE LEVEL (SUMMER OF 1908 = 581.5 FEET A.T.)

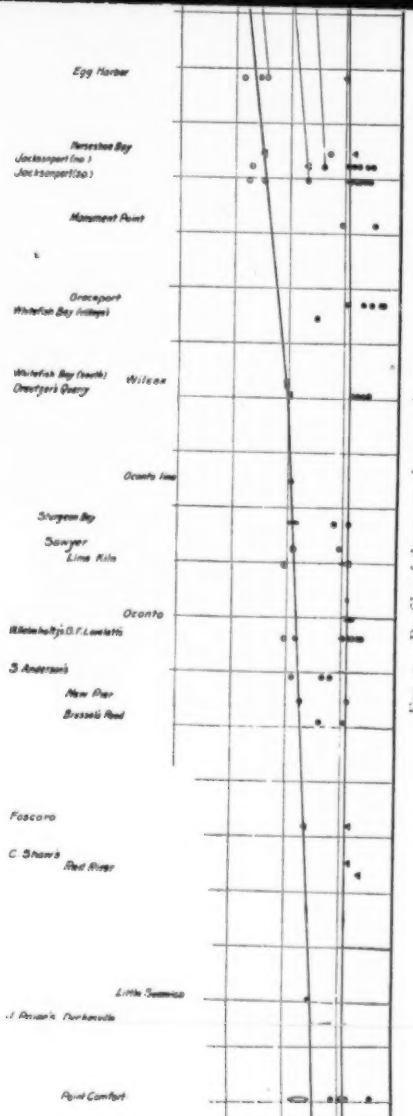


FIG. 5.—Profile of the warped water planes.

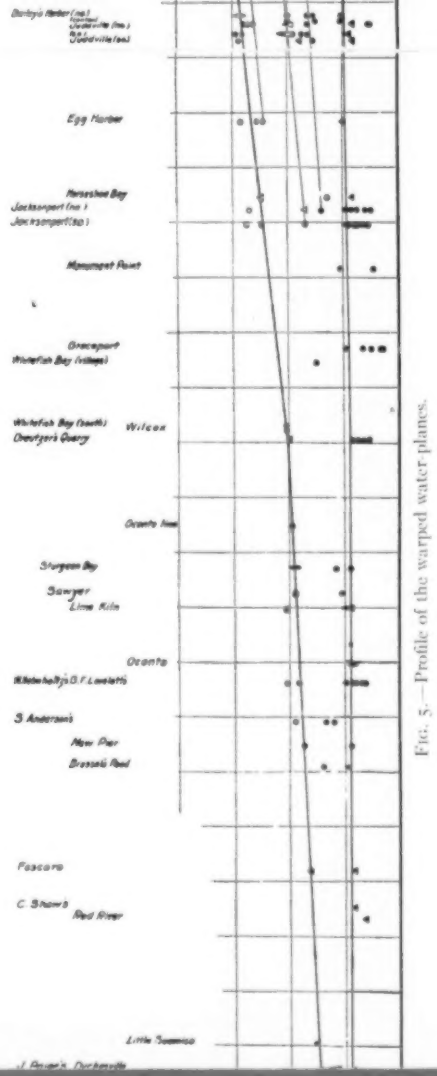
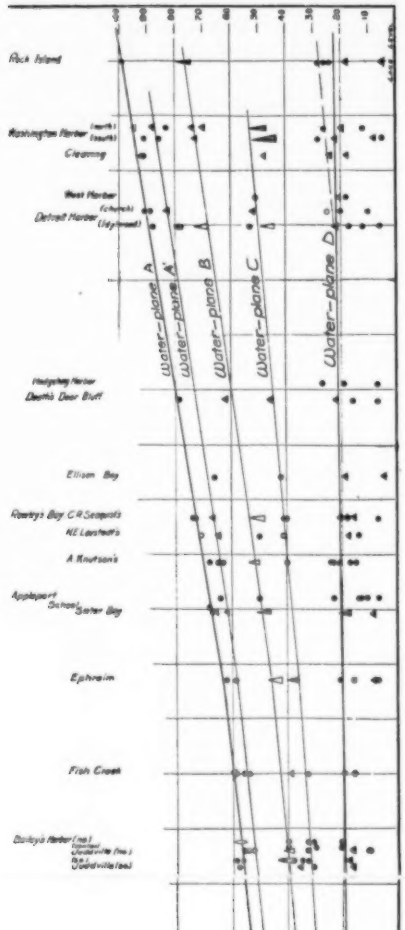


Fig. 5.—Profile of the warped water planes.


Rock Island
Washington Harbor (north) (south)
Clearing
West Harbor (Schmick)
Detroit Harbor (Heyrman)
Hedgehog Harbor
Death's Door Bluff
Ellison Bay
Rowleys Bay C.R. Seagrists
NE Lanstedt's
A. Knutson's
Applegate
School
Sister Bay
Ephraim
Fish Creek
Water-plane A
Water-plane A'
Water-plane B
Water-plane C
Water-plane D

the Port Huron outlet were running. The nearly horizontal position of this plane in eastern Wisconsin indicates clearly that very little deformation has occurred there since Nipissing time.

Below the Nipissing plane are usually several shore-lines which mark more recent stages of the lake, depending upon the deepening and widening of the present outlet. No attempt has been made to reconstruct them; but a 12-foot stage and a 9-foot stage are commonly recorded. These sometimes give rise to confusion regarding the altitude of the real Nipissing plane. Near Algoma, for instance, a very strong red-clay bluff of the Nipissing stage has at its base a terrace which is sometimes 12 and sometimes only 9 feet above Lake Michigan, but usually about 20, showing that the lake, after dropping a few feet below the 20-foot Nipissing level, easily cut back across the broad terrace to the base of the high Nipissing bluff.

EXTENSION OF THE ALGONQUIN AND NIPISSING PLANES SOUTH OF TWO RIVERS

Some difficulty attends the reconstruction of the old water-planes south of Two Rivers, for extensive cliff recession at the Nipissing and the present level has largely obliterated the record. (See Fig. 6.) No trace of a 25-foot beach ridge is seen between Two Rivers and Kenosha. High clay bluffs rise abruptly from the lake to heights above the extinct Algonquin plane, except where for short distances (as at Centerville, between Sheboygan and Port Washington, and at Fox Point) a terrace and bluff of the Nipissing stage has cut farther back into the upland. In most of the stream valleys along this distance there are terraces which mark the adjustment of streams to two and sometimes more high stages of the lake, their heights corresponding closely to the Algonquin and Nipissing planes. At Kenosha there are short remnants of a 25-foot beach ridge, and at Evanston, Ill., a strong beach ridge of the "Toleston" group of beaches of Lake Chicago runs inland at the height of 24 feet, and may be followed with occasional interruption through the Chicago district and around the head of Lake Michigan.

The flattening of the highest Algonquin plane in eastern Wisconsin, going southward toward Two Rivers, strongly suggests that it there becomes essentially horizontal. The presence of a very definite beach

ridge at the 25-foot level at those places where no cliff recession has occurred at a lower stage—viz., at Kenosha and in the Chicago district—agrees with this view. The abundance of shells in the "Toleston" beach, noted by Dr. Marcy before 1867,[1] and confirmed by other collectors since that time (including a recent discovery by the present writer in Evanston, Ill.), when contrasted with the absence of life in the 40- and 60-foot beaches, favors the idea that the Toleston or 25-foot beach marks a lake of less frigid water than the glacial Lake

FIG. 6.—Terrace and bluff of the Nipissing shore-line north of Algoma, Wis. In the foreground the old shore-line is cut away by the receding cliffs of the present lake. In the distance the Nipissing terrace is covered with a veneer of wind-drifted sand.

Chicago. Similar shells have been found in the Algonquin beaches on the west side of Lake Huron, by those working in Michigan. But of still greater significance is the fact that Mr. F. B. Taylor, Dr. A. C. Lane, and others in Michigan have found the Algonquin beach in a horizontal position in the southern part of the Lake Huron basin, 25 feet above the lake.[2] If there has been no tilting in the Huron basin

[1] See *Geological Survey of Illinois*, Part III, "Geology and Paleontology," p. 250 (1868).

[2] See *Geological Survey of Michigan, Report on Huron County*, by A. C. Lane, Vol. VII, Part II, p. 75.

south of Port Austin, as is inferred, it is probable that the same is true of the southern half of the Michigan basin, and the Algonquin beach should there be horizontal at the same altitude, 25 feet—the actual position of the highest member of the Toleston group.

The Nipissing plane can be extended in a similar way and on the basis of somewhat stronger evidence. In the region south of Sturgeon Bay the Nipissing bluffs are developed with remarkable strength, usually 30 and sometimes 80 feet high. The terrace shows an approximately horizontal attitude, descending southward at a very small fraction of a foot per mile, so that at Centerville it stands 14 feet above the lake. South of Centerville, measurements on the Nipissing terrace at Oostburg (near Sheboygan) south of Belgium, at the state line, at Zion City and Beach Station, Ill., place it within a foot or two of 14 feet. It forms a conspicuous bluff which lies just west of the tracks of the Chicago & Northwestern Railway between the state line and Waukegan, Ill. In the Chicago district, where no terraces were cut during the lower stages, an extensive series of beach ridges from 10 to 15 feet above Lake Michigan seem to mark the Nipissing and lower planes. Occasionally there is a strong wave-cut bluff, however, in the Chicago district at the 14-foot level, as at Englewood, where the low terrace is the strongest member of the "Toleston" series.

The exceptional strength of the Nipissing shore-line and the prevalence of sharply cut bluffs seem to express the gradual rising of the waters which is known to have led up to this stage in the lake history, according to the studies of Taylor and others. The evidence from Wisconsin and Illinois, therefore, seems to make the Nipissing shoreline horizontal at the altitude of about 14 feet in the southern part of Lake Michigan. Confirming this view is the evidence collected by Lane in Huron County, Mich., where a strong beach that stands 11 to 14 feet above Lake Huron is thought to mark the Nipissing plane.[1] A single observation recently made by Mr. Leverett and the present writer a few miles north of Port Huron places a strong beach, probably the Nipissing, at a height of 12 to 14 feet above the lake. Although previous observations in Michigan have suggested a slightly lower level for the Nipissing plane, it seems likely, all things con-

[1] *Op. cit.*, p. 76, and personally communicated to the writer.

sidered, that there has been the same confusion of terraces mentioned in connection with the strong bluffs near Algoma, Wis.—the upper few feet of the Nipissing terrace in many places having been stripped away at a slightly lower stage. The Nipissing plane, then, seems to be horizontal, and about 14 feet above the present lake-level in the southern parts of both the Huron and the Michigan basins.

THE LAKE CHICAGO SHORE-LINES

The terrace of the Calumet or 40-foot shore-line of Lake Chicago, traced by Alden near Belgium, Wis., was followed with some difficulty almost to Sheboygan. For most of this distance it is ill-defined, occasionally giving way to low bars; and its height seems in places to reach 49 feet. With a mile of the northern border of the Port Washington sheet, and again east of Oostburg, a gravel ridge was found 63 feet above the lake. If these fragments mark the Glenwood or 60-foot stage of Lake Chicago, they are important in extending that stage northward nearly to Sheboygan, where broad flats of stratified sand stand 60 feet above the lake. The Belgium and Oostburg 63-foot beach fragments are also important in showing that the Glenwood level persisted after a certain re-advance of the Michigan ice-lobe, which seems to have buried Glenwood beach gravels beneath a deposit of red clays near Milwaukee.[1] The fact that both the 60- and 40-foot beaches appear interruptedly nearly as far as Sheboygan, and there seem to end near a belt of rather strong morainic topography, when seen in the light of Taylor and Leverett's studies on the eastern side of the lake, suggests a re-advance of the ice in the vicinity of Manitowoc and Manistee, Mich., at the close of the 40-foot stage, overrunning for an unknown distance the northern part of the 60- and 40-foot beaches and destroying them. Further study of the beaches and moraines on both sides of Lake Michigan should make this point clear. So far as measurements were obtained on these Lake Chicago beaches, they seem to indicate a horizontal attitude, at least as far as Racine. It is possible that they rise a few feet between Racine and Oostburg.

[1] "The Delavan Lobe of the Lake Michigan Glacier," etc., U. S. Geological Survey, *Professional Paper No. 34*, by W. C. Alden, p. 69 (1904).

CONCLUSIONS

A detailed investigation of the terraces and raised beaches in eastern Wisconsin, with many measurements by spirit level, leads to the following conclusions.

1. There is a series of warped water-planes of Lake Algonquin, which rise at a moderate rate north of Sturgeon Bay, diverging, fan-fashion, until the highest is 90–95 feet above Lake Michigan at Washington Island. The divergence of these planes is interpreted to mean earth-movements contemporaneous with the Lake Algonquin stages. The tiltings seem to have decreased greatly in measure south of Sturgeon Bay, dying out in the vicinity of Two Rivers, where the Algonquin beach stands about 26 feet above the lake. South of that point the Algonquin shore-line is thought to be horizontal above Lake Michigan and represented by the highest beach of the "Toleston" group in the Chicago district, at a height of 20–25 feet, just as in the southern part of Lake Huron basin the Algonquin seems to be horizontal at a 25-foot level.

2. A shore-line of remarkable strength, usually marked by high-cut bluffs and terraces, which lies everywhere below the Algonquin sand in a horizontal position along the whole Wisconsin shore, is regarded as the Nipissing shore-line. At Washington Island this terrace is 20–22 feet above the lake; but it gradually declines to 18–20 feet at Sturgeon Bay and 16–18 feet at Two Rivers, reaching 14 feet at Centerville, at which level it seems to become horizontal and to be represented by strong 14-foot terraces in Sheboygan county, near the Illinois state line, and in the Chicago district.

3. The Glenwood or 60-foot and the Calumet or 40-foot beaches of Lake Chicago are poorly preserved north of Racine, but seem to run to Sheboygan, possibly being obliterated north of Manitowoc by an advance of the ice which formed the Manistee (Mich.) moraine.

4. If this identification and correlation is correct, one of the outlets for Lake Algonquin was the Chicago outlet, the sill of which is 8 feet above Lake Michigan. The depth of water in the Chicago outlet would have been slight after the earliest stages of Lake Algonquin, however; so the outlet at Port Huron probably played a more important part.

5. It is inferred, from the apparently horizontal position of the Algonquin and Nipissing planes in the southern parts of both the Huron and Michigan basins, that no earth-movements have affected this region since the earliest Algonquin stage, and that, if any deformations are now in progress in these two lake basins, they are limited to the more northerly portions.

THE GEOLOGIC DAY

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The fact that geologic formations, whether lithologic or faunal units, given the same name—the Potsdam, for instance—are not in all parts strictly contemporaneous, has been often noted. Terms like "homotaxial" have been applied to them to avoid the assumption of contemporaneity.

A good part of the time of the geological congresses has been devoted to a discussion of problems of a similar nature. Yet it is rarely, if ever, noted that the same problem comes up in connection with the civil day, and, in fact, with any possible measurement of time.

It has just been vigorously impressed (April 19) that 5:13 San Francisco time is not the same as Washington time, but about three hours later. Therefore the day ends and begins later at San Francisco than at Washington. The sidereal day is a little different from the solar day, the astronomical year from the civil year. The reason for this lies near to the heart of things. Time is measured by change, and change, as we know it, must progress from point to point. The progress may be as rapid as an explosion or as the transmission of light, or as slow as the precession of the equinoxes. Nevertheless, there is always a rate of progress which is measurable, and any interval of time must be marked by a certain stage in the change, and so begin differently at different points.

There is no reason to be surprised, therefore, if we find this to be true in dividing up our geological time. We measure it generally by some slow change: the evolution of life, or orogenic movements, or the accumulation of salt in the sea, the changes in sedimentation consequent on elevations of continents, or changes in climate, like the passing away of the glacial epoch.

Take postglacial time for an illustration. It is clear that the ice must have retired from the valley of the Ohio before it retired from

the Straits of Mackinac some time, and perhaps a very long time. Therefore the postglacial epoch begins later at Mackinac than at Cincinnati. Yet I do not think that it necessarily should have a different name, any more than April 18 has a different name for Europe and America. Of course, there are difficulties, just as there are difficulties in saying what is the birthday of a child born near midnight, or near the date-line in the Pacific. But they are inherent in the facts, and are not lessened by introducing new terms, which indeed may lead one to overlook the realities of the case. All these difficulties as to exact time, however, real as (for instance, to friends of the Psychical Research Society, discussing apparitions of the dying) they are at times, form but a fraction of the total application of the usual terms, "day," "year," and "hour," which are ordinarily intelligible and unambiguous. Is it not so with the geologic terms, and may we not ordinarily be justified in speaking of our Eastern and Western Niagaran by the same name as belonging to the same geologic year and coeval, even though we know one lithologic unit may have begun to form somewhat sooner than the other?

Difficulties have arisen from the fact that the lithological evidences of contemporaneity do not always agree with that furnished by fossils, and the early assumption (really a relic of the old cataclysmic theory, according to which God made one set of created beings, then wiped off his slate and began over again) was that fossils were the best and surest index of contemporaneity, in comparison with which all other factors or means of determination were of no weight.

No competent paleontologist now holds this extreme view, and many of them, like Williams, have shown clearly that fossils are not absolutely inerrant evidence of contemporaneity. Yet the influence of the old views, and the idea that the lines of a division of geological time must be lines separating different faunas, has so clung on that the tendency has naturally been, where the faunas proved misleading, to give up the idea of time entirely, and refer merely to homotaxis.

This will be a mistake. The idea of time is present in our geological divisions and their names, and though our divisions be imperfect expressions of our ideal, for that reason to throw away the ideal would be to make the same mistake as Hobbes, to whom a straight

line was merely the straightest line he could draw, and who accordingly thought he had squared the circle, because he found a construction which was correct so far as he could see. It does not follow, however, that we should give a new name every time we find evidence of real difference in geologic time in the beginning of one of our geologic divisions. It should be carefully noted, and left to be weighed and compared with other evidences, until we are ultimately able to place each division at each place accurately on a true scale of time, which shall be to the common scale as is astronomer's time to the local times and seasons of everyday use.

Of these various evidences, fossils are by no means the best evidence of strict contemporaneity. Other evidences, as good or better, are:

1. A shower of volcanic ash like that which has recently come from Vesuvius, *if* it can be identified, is one of the best evidences of contemporaneity. The same remark applies to a surface lava flow. Individual lava flows of peculiar character, like the foot of the Kearsarge lode, have been traced many miles in the Keweenawan, and great floods out West may, I presume, be equally contemporaneous. In time to come, geologists of the future may use volcanic ash-beds, among the series of shales and muds, which are overlooked now, as horizon-markers of the first importance.

2. The whole nexus of mud-flows, lavas, ash-beds, and the like, which make up an eruptive epoch, would not make so exact an index of contemporaneity, but in many cases are of considerable value. The Keweenawan, and Triassic of the Atlantic coasts are illustrations both of the value and of the danger of such correlations. While indicating real contemporaneity, if the correlation is correctly made, there is likely to be an eruption of indistinguishable rocks (or nearly so) at widely different times.

The error is analogous to that which may be made by confusing colonies among fossils; though, on the whole, with a large enough fauna there is little danger of faunal confusion.

3. A change of climate may extend with great rapidity over a province or over a very large part of the world. The glacial period in Europe and America is one glaring illustration. Another is the change in the Carboniferous from the hot, dry climate of the Mis-

sissippian to that of the Pennsylvanian. The change may, of course, have occupied considerable time in its spread, but probably only a fraction of the duration of each period. Salt beds, whether formed in desert wastes or inlets of the ocean, point to a dry climate.

4. If one could only get samples of water in which the strata were buried which had not changed in the meantime, one might, in the case of open marine strata, be able to date them from the progressive change in the character of the sea water. This may be of more value in the future than in the past, as it probably can be used only on water carefully preserved from deep borings in slightly disturbed synclinals where numerous beds are impervious.

5. Changes in the elevation of the land, and consequently in the shore-line, produce changes in the sedimentation in which climate may co-operate. These changes in the sediment-determining factors may be slow, like the tilting of the basin of the Great Lakes, now going on. But even in such cases they may be nearly simultaneous over long stretches of shore-line. They may also be sudden, like the uplifts of the South American coast described by Darwin and numerous other earthquake disturbances. In general, it may be said to be likely that a sudden change, involving the injection of fine mud in the ocean water, is not likely to be extremely local.

As a result of these changes, the fauna is driven hither and thither, and more or less modified by the stress of circumstance.

If the difference in sedimentation slowly progresses, it is quite possible that the corresponding change of fauna will be equally slow in spreading from point to point. Thus, in determining what is really genuinely coeval, there is often no reason to prefer the evidence of fossils to that of sedimentation, if all the factors of the early geography are duly taken into account.

The great advantage that the fossils have is that they never come back to their original combinations. The course of life has never really gone backward, whereas sandstones, limestones, and shales of recent times may be undistinguishable from those of earlier times. Thus, when it comes to determining the general place in the geological column, to deciding whether the Lake Superior sandstone was "New Red," "Old Red" or coeval with the Cambrian, fossils, if obtainable in sufficient quantity, far outclass other kinds of evidence.

But when it comes to minute comparison, they are by no means exclusively to be trusted. If we find ourselves following along the shore-line of an older, settling land-mass, and there are indications that the land settled as a whole without tilting, or that, if it tilted, we are still following one coeval shore-line, which was the farthest extent of the overlap of the time, we may often be sure of a good degree of contemporaneity, independent of fossils. Of course, if we regard black shales as colored by pollen and spores, it may be said that the black shale is a faunal characteristic. But if we disregard the species and genera of spores, it becomes a mere physical characteristic, dependent on climate, like a bed of salt. Then we may fairly ask if the physical change which leads to the sudden appearance of a bed of black shale above a limestone (like the Marcellus above the Corniferous) is not likely to be closely contemporaneous over a wide area. We may extend such illustrations indefinitely. The point that I would make is that, while the paleontologist can sometimes draw fine lines of time-division, a careful stratigrapher, a paleogeographer, can at times draw equally valuable lines of time-division, as nearly the same in different places, relatively to the lengths of the intervals separated, as the divisions of civil time.

If objection is made to using paleontology for the larger and broader time-determinations, and using various other methods for details, and not always drawing the line at the same place in using terms applied to these divisions in the different regions, we can again fall back on the analogy with the divisions of common time, where the sun rules the year, and the moon long ruled the month, while the finer and more exact divisions depend on other data, and the year does not begin or end exactly at the same time at every place.

STUDIES FOR STUDENTS[1]

RELATIVE GEOLOGICAL IMPORTANCE OF CONTINENTAL, LITTORAL, AND MARINE SEDIMENTATION

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PART II

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THE REGIONS OF MARINE SEDIMENTATION

For the present purpose it is unnecessary to consider the deep ocean deposits, or even the massive limestone formations, since the discussion centers on the comparison of the areal extent and importance of the detrital deposits upon the land and beneath the sea.

The investigations of the Challenger expedition[2] showed that the rubble, sand, and silt were practically limited to the upper 100 fathoms of the ocean bed, and that this corresponded rather closely with the limits of the continental shelves. At about this depth the bottom is in general rarely disturbed by the action of currents or waves. Except in bays, fjords, and inclosed seas where mud is met with in shallow water, it may be said that in general, fronting all

[1] Continued from p. 356.

[2] Murray, *Deep Sea Deposits*, p. 184.

open coasts, 100 fathoms is the average depth at which fine mud or ooze commences to form; but local exceptions may be noted. In general, the cleaner sands are restricted to a belt within 30 miles of shore, and the average limit of the blue muds is about 200 miles, though this varies greatly in different regions. The relation of these terrigenous to the true pelagic deposits is well brought out in Chart I, *Deep Sea Deposits*, Challenger Expedition. This area of marine deposits of land-waste is etimated to cover about one-seventh of the globe and to be equal to half the area of the continents, while the area within the 100-fathom line, which more immediately concerns the present subject, is estimated at 10,000,000 square miles, or about one-fifth of the continental areas.

The deposits of former ages corresponding to the shallower and deeper portions of the terrigenous zone may be distinguished by a number of textural and structural features. For instance, considering the conditions of present deposition, it is seen that the ancient equivalents of the present blue muds will be rather widely extended, uniform, massive, argillaceous deposits, usually slightly carbonaceous and grading into calcareous formations. They will be without cross-bedding and ripple-marks, since movements sufficient to form these would prevent the settling of muds. They may be distinguished from ancient estuarine muds by all these features, and especially the absence of frequent alternations of sand. It is doubtful, however, if the deeper portions of these blue muds have ever been elevated into land surfaces. On the other hand, the shallower belt of marine deposition will be marked by a sandy character of deposits, provided that the rocks of the land can furnish sand, by evidences of shifting current-action and by ripple-marks. A. R. Hunt has shown that the waves of storms may stir the sands of the bottom to a depth of 40 fathoms sufficiently to move gravel and injure living molluscs.[1]

The charts of the United States Coast and Geodetic Survey also show sand and comminuted shells to similar depths, from which it may be inferred that widespread arenaceous and unfossiliferous formations may be formed on the bottoms of shallow seas, and not necessarily in close proximity to the littoral zone.

[1] "On the Formation of Ripple Marks," *Proceedings of the Royal Society of London*, Vol. XXXIV (1882), p. 1.

Approaching the shore, the material of the shallow bottom becomes coarser and ends in the undertow slope of the beach. This is sometimes coarser than the material of the beach itself,[1] stones of a certain size being swept here by the undertow and only carried back to the beach by the heavier storms. It is to be concluded, therefore, that one of the most striking characteristics of ancient beach-action, a basal conglomerate, is hardly so much a mark of littoral deposition as of marginal marine deposition *bordering* the true littoral zone.

As river deposits of delta surfaces, on the one hand, tend to extend themselves both by building forward into the sea and by building backward over the land, so, on the other hand, marine deposits, as Chamberlin has pointed out, tend to extend themselves in both directions.[2] Toward the deep ocean basins the clays are swept and deposited near their brink, doubtless building out submarine deltas, as is suggested by the submarine platforms of the Caribbean Sea.[3] and by the hypsographic curve of the earth crust given by Penck.[4] In the opposite direction the waves are always at work upon the coast, and tend to cut the sea-cliff landward, except where the supply of material from the land is equal to that removed by the sea. As the wave-beaten material is rolled backward and forward, it is gradually reduced to a fineness where the undertow can sweep it away from the beach-action and allow it to finally settle at some little distance from the land. The result of these activities within the upper portions of the ocean is to cut back all headlands, to fill up recessions in the coast line, and to cut away all islands except where these have been thrown up as barrier beaches by the sea.

The rapidity with which the waves may cut into unconsolidated material has been frequently illustrated by the destruction of recent ash-cones, which in a few months or years have completely disappeared. Barrier beaches, the only form of islands tolerated by the sea, are thrown up where the waves drag and break in shallow

[1] Dana, *Manual of Geology*, p. 223.

[2] T. C. Chamberlin, "The Ulterior Basis of Time Divisions," *Journal of Geology*, Vol. VI (1898), p. 454.

[3] Bailey Willis, "Conditions of Sedimentary Deposition," *Journal of Geology*, Vol, I (1893), pp. 496, 497.

[4] *Morphologie der Erdoberfläche*, Vol. I (1894), p. 136.

water, and can attain any degree of permanence only where they face a gently shelving land mass.

The waves not only tend to unify and extend the shallow submarine platform, but tend to cut away its highest portions to a certain depth, dependent upon the power of the waves. Thus, by taking nautical charts it is observed that over any district where there is open water the bottom maintains a certain depth close up to the off-shore beach. Facing the open oceans this is usually from 30 to 40 feet, but in more protected places, such as Long Island Sound, it may be but 6 to 12 feet. Thus, up to the line of surf the submarine platform extends without any confusion with the littoral zone.

EXTENT AND CHARACTER OF THE LITTORAL ZONE

The littoral region, as has been shown, is rather sharply delimited from the marine by the trimming action of the sea, marked along a shelving shore by the line of barrier beaches. Where a bold land meets the sea, it is merely the lowest exposed portion of the sea-cliff. On the landward side, however, the littoral is not so regularly defined, but consists of irregular tidal lagoons consisting of three portions; the mud-flats, exposed at low tide, the salt marshes flooded only at high tide, and a rather abrupt transitional mud-slope between them. Both the mud-flats and tidal marshes are cut through by tidal channels, those on the marsh being characterized by meanders.

The littoral finds its greatest development in estuaries or where the land meets the sea in the form of a plain, either a base-plain of erosion, or a river plain of aggradation. The littoral does not show a tendency, like the two previous regions, to extend its limits, since the flood-tide tends to leave sediment upon the tidal marshes, building them up to the extreme tidal limit; and, on the other hand, the tidal scour of ebb-tide tends to remove sediment to the open sea. On the contrary, the forces of both land and sea tend to fill up and obliterate the littoral. On the one hand, the river deposits and the wash from the land creep out over the tidal flats, and, on the other, the sea, by wearing the beach deposits smaller and by removing the finer shore material outward to a greater depth, tends to push its beaches farther inland.

The littoral zone is partly maintained by the contest of the two

forces—the rivers building out by irregular delta mouths, inclosing lagoons and providing new tidal marshes; the sea cutting off headlands and sweeping the material along the coast, forming spits which shut off new lagoon spaces.

The chief maintenance of the littoral belt is, however, due to vertical land movements, especially subsidence of a flat land surface, but one still showing slight relief. This may produce extensive estuaries, and the waves, by throwing up barrier beaches in shallow water at some distance from the land, may form a continuous series of lagoons and salt marshes, as is illustrated by the present condition of the seaward margin of the coastal plain of the eastern United States from Long Island southward. The questions of immediate importance in the present connection are those of the width and areal extent of the littoral zone and possible fluctuations in importance in past times, owing to the prevalence of conditions not now operative, such as absence of tides in ancient protected seas, or hypothetically greater oceanic tides due to a possibly greater nearness of the moon. It is first necessary to collect the facts for the argument, by observing the various shore conditions as they exist today. Arranging these with respect to the tidal range, a representative set is as follows, the information being taken largely from the charts of the United States Coast and Geodetic Survey:

OBSERVED RELATION OF TIDES TO THE LITTORAL ZONE

TIDE 1 TO 1.5 FEET (EXAM. MOBILE BAY AND MISSISSIPPI DELTA, GULF OF MEXICO; STORM TIDES THE ONLY IMPORTANT ONES)

Mud-flats at mean low tide, 0.1 to 0.25 mile wide in protected places.

Salt marshes.—Frequently absent. Around Mobile Bay a few up to 2 miles wide. On the delta of the Mississippi (General Chart No. 19) they average 27 miles in width, cut through by the fresh-water channels and showing a poorly developed system of channels for tidal drainage.

TIDE 2.5 FEET (EXAM. GARDINER'S ISLAND AND OYSTER PONDS)

Mud-flats few in number. At mean low tide 0.33 to 0.66 mile wide in protected places.

Salt marshes average 0.25 mile wide.

TIDE 4 TO 6 FEET (VICINITY OF NEW YORK AND NEW HAVEN)

Mud-flats from 0.16 to 0.33 mile wide, of limited development.

Salt marshes in protected inlets behind barrier beaches 0.5 to 1.0 mile wide.

Along river valleys, as north of Newark Bay, they extend some 3 miles from the open water, passing into the fresh-water marshes. Tidal channels fairly well developed upon marshes.

TIDE 7 FEET (SAVANNAH, GA., ENTRANCE TO SAVANNAH RIVER)

Mud-flats 0.33 to 0.66 mile wide. More commonly present than in previous examples.

Salt marshes filling up a former estuary, 4 to 5 miles wide, with a well-developed network of tidal channels ramifying through them.

TIDE 10 FEET (BOSTON HARBOR AND DELTA OF THE INDUS RIVER)

Mud-flats extensive. At Boston they average from 0.5 to 1.0 mile wide, but are cut up by tidal scour into smaller separated areas.

Salt marshes.—At Boston, filling up protected depressions, they average 0.25 to 0.75 mile wide. On the Indus delta a well-developed network of tidal channels, 2 to 4 fathoms deep, and distinct from the distributaries of the river, extends 17 miles from the coast, and this may be taken as the limit at which the salt-water tidal marsh gives place to the fresh-water swamp. Tide reaches 11 feet in spring tides.

TIDE 16 FEET (DELTA OF THE GANGES AND BRAHMAPOOTRA)

Mud-flats.—Extent not mentioned.

Salt marshes.—Extent indicated on the map by means of the tidal channels (see reference later). The fresh-water swamps of the delta are protected from the sea by a chain of sandy islands, separated from each other by tidal channels and known as the *Sunderbuns*, the name evidently signifying severed mounds. This chain of islands averages 58 miles wide, but only the outer half is markedly cut up by tidal channels. Therefore it seems probable that the present tidal flooding extends some 30 miles inland, and the inner portion may have been built at an earlier date. Tidal effects on rivers are of course felt much farther but do not flood wide stretches of their banks.

TIDE 40 TO 70 FEET (BAY OF FUNDY, BASIN OF MINAS)

Mud-flats.—Widest in protected heads of bays. In the basin of Minas, estimated by J. A. Bancroft to average 0.75 mile wide. Along sides of the bay the current of from 6 to 8 miles per hour keeps the channel deep and open, and the sides scoured clean.

Salt marshes.—Shaler speaks of the dominance of the mud-flats over the upper marshes, and the rapidity with which the latter are built up by sediment thrown down at flood-tide when obstructions are built across the tidal marshes. Lyell speaks of thousands of acres having been reclaimed in this way.

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Charles Lyell, *Travels in North America*, Vol. II (1855), p. 166.

N. S. Shaler, "Sea Coast Swamps of Eastern United States," *Sixth Annual Report* (1885), United States Geological Survey, p. 368.

J. A. Bancroft, "Ice-Borne Sediments in Minas Basin," *Proceedings and Transactions*, Nova Scotian Institute of Science, Vol. XI (1905), Part I, p. 161.

From the preceding facts a number of principles governing the development of the littoral zone may be drawn.

With lunar tides of less than 2.5 feet storm tides become of greater importance. The development of extensive mud-flats and salt marshes takes place in protected places. In exposed places the cutting action of the waves prevents either from forming. Mud-flats exposed at low tide become conspicuous with tides of about 6 feet range. When the tide is 10 feet, these may form belts a mile wide, but broken up by tidal channels. With higher tides there is but little tendency to increase the width of exposed flats, but the material constituting them may become coarser, the Gallegos River in Patagonia, where the tides reach 46 feet, showing lower flats composed of gravels and even of coarse bowlders.[1] With the larger tides the tidal channels for draining the tidal marshes are wide and deep, forming convenient protected passages for the larger vessels through silted-up estuaries or behind the barrier beaches.

The salt marshes are built up to near the upper limit of tidal flooding. Where storm tides are the most important the system of drainage of these marshes is very imperfect. With tidal range of from 4 to 6 feet this becomes developed, and with a range of from 10 to 16 feet they become rivers in size, capable of quickly leading an immense volume of water into the limits of the tidal area, but more important for quickly draining the tidal grounds during the ebb. The width of the salt marshes appears to be less dependent

[1] J. B. Hatcher, *Princeton Patagonian Expeditions*, Vol. I, Fig. 33, and p. 239.

upon the tidal rise than upon the greatness of the river and its delta which faces the tidal wave. This may be due to the great quantity of sediment furnished to the sea by the rivers, swept back by the tide and dropped at its flood, or to the subsidence which frequently characterizes such areas and which tends to drown the seaward end of the delta. Probably both causes contribute. This is illustrated by noting that on the Mississippi delta this width of marsh is 27 miles, while in Mobile Bay near by it is from nothing up to 2 miles. At Boston the marshes average less than a mile in width, while the Indus delta, with the same tidal range, shows them at least 17 miles wide. The delta of the Ganges in the presence of a tide of 16 feet is flooded by the tides for a distance of 30 miles, while in the Bay of Fundy and the Basin of the Minas the salt marshes average less than a mile in width.

The conclusion is geologically of some importance. The broad development of a littoral zone is largely independent of tidal influence, since, where the tides are small, oscillations of level through storms may develop it to practically the same width. The topographic character of the littoral zone, as indicated by dominance of mud-flats, size of tidal channels, etc., is, however, dependent upon the tidal range as one factor. Where the land is shelving, as along the eastern and southern coasts of the United States, the shore may be much broken with estuaries, but the land and the water are separated by a littoral, which, including both its upper and lower portions, does not average more than a mile in width. The littoral is therefore of insignificant area compared to the breadth of the coast plains on the one hand, and of the shallow sea on the other.

The littoral becomes broadest where a great quantity of sediment is poured into the sea by a great river and a contest ensues between the sea and the land. But in such places the river, if sufficiently powerful, builds out a land surface delta in the face of the storms and tides, while the undertow of the latter builds out another extensive platform, submerged in gradually deepening water, and ending where a depth is attained of from 50 to 100 fathoms. Even beyond this limit important quantities of the finer sediment are swept, forming occasionally bottom deposits from 200 to 800 miles from land.

It is seen, therefore, that in places where the littoral attains a maximum width of 30 miles there are at the same time far greater areas receiving land and ocean sediments, so that the proportion of the littoral zone is hardly greater than before.

These few places where the littoral attains a maximum width are offset by the thousands of miles of coast-line where the sea is cutting into the land, and the tide rises and falls against a narrow beach at the foot of a sea-cliff; so that the previous conclusion may be further extended to include all continental coast-lines; and it may be stated that, taking the world as a whole, the width of the littoral zone does not average a mile, and therefore comprises but a small fraction of the earth's surface compared with the great extent of marginal marine and even of continental deposits.[1]

With respect to the shallow-water marine formations this remains true under all geological conditions, and therefore remains true for all geological time. But occasionally, in periods when the continental surfaces were physiographically old, of greatly diminished area and supplying but little sediment, continental deposits may well have sunk to less importance than the littoral. During such periods, however, there is a corresponding expansion of epicontinental marine sediments, though at such times of a calcareous character, so that the insignificant proportion of the littoral to the sum-total of other sediments deposited upon the continental platforms would not be greatly changed, and has been a constant feature of the earth's surface.

CAUSES RESTRICTING THE WIDTH OF THE LITTORAL ZONE

The previous examination of open sea and estuarine coasts shows that the width of the littoral is not dependent merely upon the flatness of the shores, nor upon the magnitude of the tidal range. These, while contributory factors, can operate only within certain limits. In order to see why this is so, it may be well to state briefly some of the causes which influence the result.

1. The influence of varying slope of shore may be seen in Fig. 5.

[1] Chamberlin and Salisbury, *Geology*, Vol. I, p. 352, give the width of the littoral zone as half a mile, the length of the coast-lines of the world as 125,000 miles, and consequently the area of the littoral zone as 62,500 square miles, as against 10,000,000 square miles for the area of the shallow-water zone within the 100-fathom line.

Suppose that the shore, to begin with, is a smooth, gently inclined plane, represented in cross-section by *OB* or *OC*. The level of low tide being *OD*, the volume of water passing *O*, the lowest part of the littoral, will be represented in the one case by the triangle *OAB*, in the other by the triangle *OAC*. But the areas of these triangles are to each other as their bases *AB* and *AC*. Hence in this ideal

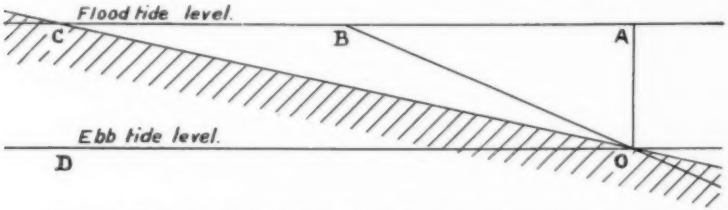

FIG. 5.—Diagrammatic relation of the width of the littoral zone to unadjusted slope of land surface.

case the volume, and consequently the mean velocity, of water flowing past *OA* will vary directly with the width of the littoral zone. But Révy has shown that the average velocity is an arithmetical mean between the bottom and surface velocities, and that the swifter the current, the more nearly the bottom velocity approaches the mean.[1]

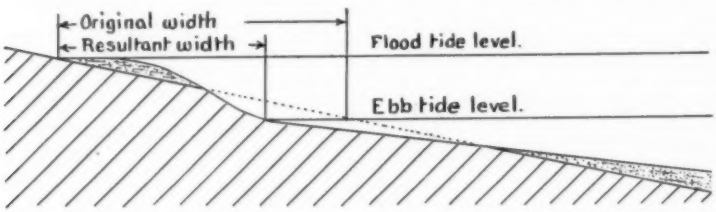

FIG. 6.—Diagram of littoral zone adjusted to slope, wave work neglected.

Therefore the bottom velocity increases somewhat faster than the width of the littoral in the ideal case. But the eroding ability of water varies as the square of the bottom velocity and the transporting ability as the sixth power. On an originally flat shore the mid-tide would consequently possess such scouring power for some distance on each side of the original low-tide limit that, as shown in Fig. 6,

[1] *Hydraulics of Great Rivers* (London, 1874), p. 147.

the bottom would be cleaned out, part of the detritus swept to the upper tidal limit and deposited, while a larger and coarser part aided by the downward grade would be swept seaward by the ebb-tide.

In nature the land slope is never smooth, and the discharge of the ebb-tide is concentrated along those lines which give the quickest egress and the greatest depth of water, the result being the building up of tidal marshes in protected places, the scouring of tidal channels, and the formation of extensive flats chiefly below the level of low tide. In these ways an originally widely extended littoral zone would be narrowed to a certain stable width for a given height of tide. The above discussion neglects the action of waves, chiefly operative at the upper and lower tidal limits, in exposed situations.

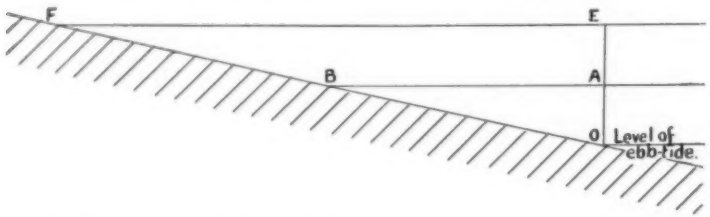

FIG. 7.—Diagram to illustrate relation of littoral zone and tidal scour to height of tide.

2. The influence of varying height of tide may be seen in Fig. 7. Letting *AB* and *EF* be the respective upper limits of tides on a recently invaded shelving shore: the volumes of water flowing past the low-tide limit will be as the areas of the two triangles *OAB* and *OEF*. But these being similar, the ratio of the areas will be given by the ratio of the squares of similar sides. Consequently, the volume, and with it the mean velocity, of the water invading the shore varies at the line *OE* as the square of the height of the tide, *OA* or *OE*. But Révy has shown that as the depth of a current increases the bottom velocity approaches more nearly the mean velocity, until in great depths and in strong surface currents they are substantially alike.[1] *Therefore on an ideal newly formed shore the bottom velocity past the point of low tide will increase somewhat faster than the square of the height of the variable tidal rise.*

[1] *Op. cit.*, p. 148.

The result as observed in nature is an added scour in regions of high tides by which the bottom is cut away, tidal marshes at the heads of bays or other suitable places are built with great rapidity, and these are dissevered from each other by tidal channels draining the marshes, which in the more striking cases may be sufficiently deep and wide even at low tide for the purposes of commerce. In time, if subsidence does not take place, the tidal marshes become raised by accretion through æolean and organic action until reclaimed from the sea, and the littoral zone is diminished as before to a certain stable width.

CONDITIONS FOR PRESERVAL OF THE SEDIMENTARY RECORD

It has been seen that in the making of the sedimentary record but an insignificant portion would be contributed by the littoral zone. There are still, however, two factors to be considered—that of the preserval of the record, and that of its ultimate exposure to observation through partial erosion.

In order to become part of a permanent geological record, the sedimentary structures must be preserved without obliteration, first, until buried and lithified, and, secondly, indefinitely protected from erosion until some new cycle of activities proceeds to destroy it and while so doing transitorially exposes it to observation.

PRESERVAL OF THE CONTINENTAL AND MARINE RECORDS

In regard to the river sediments, slow subsidence of the region or elevation of an adjoining region is necessary for their continual formation. Each layer of sediment from the flood waters is laid down upon the previously dried and hardened layer, and there is therefore not much tendency to erase the record made on the previous surface except in the lines of the channels. Soil beds, swamp deposits, mud-cracks, and ripple-marks are consequently abundantly recorded in fluviatile formations. Unless, however, subsidence carries at least the basal portions of the deposits below the ultimate base-level of erosion, the formation will be finally destroyed, as is illustrated by the present erosion of the Tertiary river deposits of the Great Plains facing the Rocky Mountains. In river deltas, however, the proper conditions are observed to occur. Here the upper limits are but

slightly above the level of the sea, and subsidence in such regions is observed ordinarily to go forward with accumulation. This will indefinitely protect the formation until some new and adventitious geological activity reverses the processes which resulted in the accumulation.

To sum up, then, it is seen that the geological processes which result in the accumulation of desert deposits, if carried to their limit, will ultimately destroy those same deposits, as Passarge has recently shown.[1] The same is apt to be largely true of Piedmont plains of river deposits; but in the case of interior basins, and more especially in deltas, the conditions are most favorable both for temporary and ultimate preserval of the land-surface record.

The same is, of course, true of the record made on the ocean bottom, since this is normally the region of deposit and not of erosion.

CONDITIONS FOR PRESERVAL OF THE LITTORAL RECORD

In regard to littoral deposits it will be seen, however, that the chances are frequently unfavorable for the preserval of its deposits until burial.

1. On an emerging land, such deposits would form a surface veneer and be the first layer to suffer erosion, before even a chance for lithification had occurred.

2. On a stationary or slightly subsiding coast, where delta deposits are encroaching upon the sea, the fresh-water material will fill up the estuaries and lagoons, covering and preserving their records, and crowding the beaches farther out to sea. The littoral deposits in that case would be preserved as old beach, lagoon, and estuarine deposits transitional, in a vertical section, between the off-shore marine deposits below and the fresh-water land-surface record above.

3. Where an old land surface is slowly subsiding, the weak erosive power of the upper portions of the rivers is no longer able to supply sediment for building out deltas against the sea, and there is, on the contrary, a transgression of the sea across the land. Assuming that the land surface slopes gently seaward, the depth of the littoral deposits behind the barrier beach where such exists cannot in general

[1] "Rumpfflächen und Inselberg," *Zeitschrift der deutschen geologischen Gesellschaft*, Vol. LVI (1904), Protokol., 193–209; review by W. M. Davis, *Science*, Vol. XXI (1905), p. 825.

be as great as the depth of the sea in front. The advancing sea will therefore tend to cut away and destroy whatever littoral deposits may be made in advance of it, as illustrated in Fig. 8*A*. Observations confirming this statement may be occasionally made along a subsiding coast, as that of New England. To illustrate, Boston is found to be sinking at the rate of a foot a century and New York City, according to the most recent estimates, at the rate of 1.5 feet per century.[1]

That the coast between the two cities participates in this movement is indicated by the sharp boundaries of the salt-water marshes.

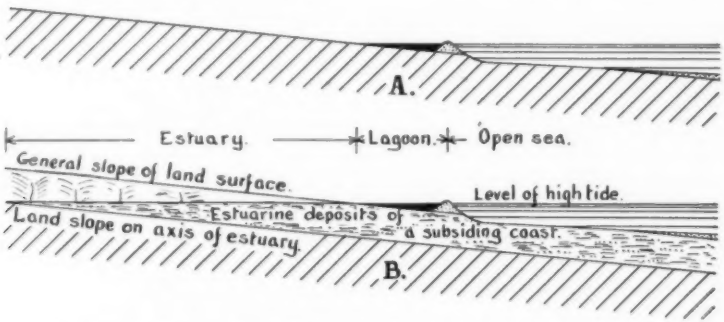

FIG. 8.—*A*, diagram illustrating progressive destruction of littoral deposits by marine planation over a subsiding land. *B*, cross-section on line of an estuary, illustrating part preserval of estuarine deposits during the transgression of the sea over a subsiding land.

These extend sharply to old alluvial slopes which rise at gentle angles from beneath them without any belt of fresh-water meadow being found between. If the land had been stationary for many centuries, the wash from the land, aided by the sediment from the highest tides, would have raised the border somewhat above the salt-marsh level. The opposite condition of affairs indicates therefore continual subsidence, but at a rate so slow that the organic and inorganic detritus, held by the roots of the marsh grass, is able to accumulate with sufficient rapidity to keep the surface at about the level of mean high tide.

A particular instance where the beach may be observed cutting

[1] G. W. Tuttle, *American Journal of Science*, Vol. XVII (1904), pp. 333–46.

away the older lagoon and marsh deposits may be cited from unpublished observations of Mr. I. Bowman. This is 2.5 miles south of Scituate Harbor, Mass., between the third and fourth cliffs, where the beach has retreated inland from 225 to 300 feet since 1898. The beach ridge is of pebbles, from 100 to 125 feet wide at mid-tide and from 8 to 10 feet above the level of the salt marsh behind it. In consequence of the rapid retreat, the marsh material at present shows at mean and low tide on the *seaward* side of the beach, illustrating the tendency of the sea to cut away the littoral as it advances upon the land.

There are a couple of ways, however, by which littoral deposits may be preserved upon a subsiding flat land. The first is illustrated by the unequal beach-cutting observed along the New Jersey coast.

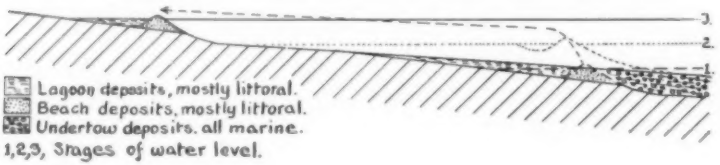

FIG. 9.—Cross-section illustrating occasional preserval of littoral deposits by building up of a beach, stages 1 and 2, without landward movement during land subsidence.

At Long Beach the sea has cut the lagoon space entirely away and is fronted by bluffs. Farther southward the barrier beaches begin and shut off Barnegat Bay. There is known to be a lateral transfer of beach material southwestward along the Atlantic coast. By this means it is possible for an offshore beach to be built up vertically as the coast subsides, the lagoon space behind broadening and deepening, as shown in Fig. 9. Finally, when the lateral supply of material ceases through recession of the bluffs, the beach will be rapidly transferred inland, but the depth of wave-planation may not reach to the bottom of the marsh deposits.

Again, the shore will be more or less indented with shallow river valleys turned into embayments or estuaries, and in these a greater depth of littoral and estuarine deposits may accumulate, and partly escape the marine transgression and planation which ensue with further subsidence. The protective effect will be slightly diminished,

however, by the incurving of the spit-bars thrown partly across the mouth of the estuary. Illustrations of this nature are well exhibited along the Atlantic coast of the United States. As seen in cross-section, the bottom line of Fig. 8*B* represents the center line of the estuary bottom, while the depth of the marine planation is determined by the average slope of the land.

In the sedimentary record made, therefore, upon a subsiding land, only a fragmentary littoral record should be preserved at the base, and upon tracing the formation laterally there should be frequent places where the marine off-shore sands, gravels, or conglomerates should rest directly upon the old land surface. This contact of true

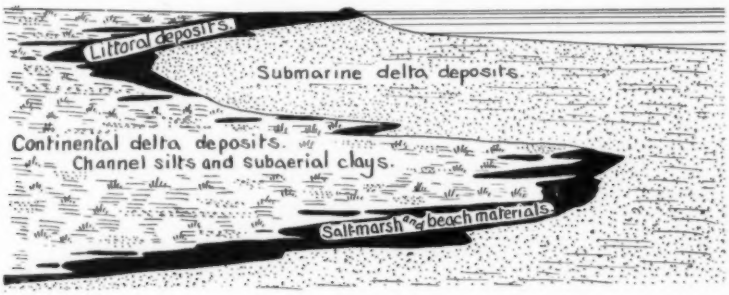

FIG. 10.—Ideal cross-section of a delta, showing geological relations of fluvial, littoral, and off-shore deposits. Vertical scale much exaggerated.

off-shore marine deposits with the old land surface seems to be the common rule observed upon that most striking of American transgressions, that of the middle and upper Cambrian, across the greater portions of the North American continent, though Dana[1] states that the beds "are in part beach made and wind made sandstones, ... and the layers often bear ripple-marks, shrinkage cracks, worm burrows, and, in some places, tracks of animals." The shrinkage cracks may doubtless be taken as good evidence in this instance of a littoral origin.

To sum up, it is to be expected that littoral deposits should be found dividing former land surfaces from sea bottoms, commonly present where the land surface is represented by subaërial delta

[1] *Manual of Geology*, p. 464.

deposits and comprises the *overlying* formation; frequently absent where the old land surface, ordinarily a land erosion surface, *underlies* the marine deposits. The littoral zone is small in local area compared with the occasional delta deposits which border it on the one hand, and the universal marine deposits which border it on the other. As seen in vertical section, therefore, the littoral deposits should have but limited lateral development on any one horizon. If the movement has been the subsidence of an old land, they should not be again encountered in the superior strata, but in the case of the contact of a delta with an epicontinental sea the littoral zone, as shown by the diagram, Fig. 10, might move backwards and forwards as a zigzag line through the vertical section, representing the advance and retreat of the sea as the subsidence on the one hand, or delta-building on the other, dominated at the moment, the littoral deposits dividing the marine from those made upon the surface of the land.

RELATIONS OF CONTINENTAL AND MARINE SEDIMENTATION THROUGH GEOLOGICAL TIME

In the preceding discussion the relative importance in area and volume of modern land, seashore, and shallow-water marine deposits has been discussed. It has been seen that the littoral zone occupies the least area and stands the smallest chance of preserval, while land deposits of various sorts hold second place; most important among these, on account of their favorable chances for preserval, being river sediments, made in interior basins, or as deltas encroaching upon the sea. The marine detrital deposits of the continental margins are, however, the most widespread and important of the three classes.

In discussing these relations they were seen to be dependent upon many broad features, such as the degree of continental uplift and areal extension, recency and magnitude of mountain movements, climatic zones, and other such factors. These have varied widely, however, through past time, and while the geographic details of former ages are largely wanting, still the general character of the terrestrial surface is in a manner known; as, for example, it is known that the Triassic over every continent was in general characterized

by broad continental uplift, orogenic movements, and variegated climates, while the Jurassic was, on the contrary, characterized by a spread of epicontinental seas, less rugged and elevated land-masses, and warm, equable climates extending into the polar regions. This conception of world-wide conditions characterizing the several ages, and distinguishing them from each other must, according to Chamberlin, form the ulterior basis of time-divisions and the classification of geologic history. But if the several ages have been characterized by certain relations of mountains, plains, and seas, then they should also be characterized by the kinds of deposits made under these conditions. The most natural method of testing this question would be to study all of the formations of the world belonging to a certain age, and group them according to area and origin. This has been done, and it is the method by which the conclusions in regard to the broader features have been arrived at. But as the very subject under discussion involves the possible confusion of certain unfossiliferous littoral and shallow-water marine deposits with those made upon the land, this method must be reversed, and by basing the arguments upon the known continental relations, as determined by formations in regard to which there is no doubt, conclusions may be reached in regard to the relative importance of deposits of those three classes which should characterize the different ages. This may be of value in suggesting discriminations not otherwise thought of, but it is not the purpose to offer here criteria for finally and definitely testing the origin of any particular formation. The latter question must, of course, be finally settled by a detailed study of the formation in the field and in all its aspects.

As introductory to this discussion it may be well to restate briefly certain of the principles which are found to govern the development of several classes of deposits at the present time.

Where young and lofty mountain ranges stand sharply above the surrounding country there will be much local waste on the Piedmont plains at their feet. If at least one slope faces the interior of a continent, this will result in extensive continental deposits, perhaps accentuated by conditions of aridity. Down-warped interior basins may also receive deposits. For effective delta building, however, there must be a submerged continental platform, or epicontinental

seas, and Chamberlin has pointed out[1] that the effect of the greater earth-movements has been to temporarily reduce to a minimum these shallow submerged portions of the continent. Such movements of continental uplift, or rather down-sinkings of the ocean basins, seem, however, to carry up portions of the crust to heights notably above the plane of isostatic equilibrium, from which they gradually settle back toward equilibrium by virtue of the slow fluency or quasi-fluency of the rocks.[2] At the same time, base-leveling is proceeding from the margins of the continents, reconstructing new coastal shelves, whose edges tend to become submerged both by the slight filling of the sea with sediment and by the settling back of the continental platforms. Assuming the truth of these general laws of major earth-movements, subaërial delta-building encroaching upon the shallow seas would attain greater importance as the erosion verged toward maturity, since the amount of landwaste increases; the streams, now being graded, carry it through to the shores, and submerged continental platforms have had time to form. At the same time, the deposits of arid interior basins and of Piedmont slopes will diminish in importance, and finally become more or less eroded.

Finally, as the continent becomes topographically old, the mountain slopes become subdued, the burden of the rivers lessens, they can no longer build out extensive deltas against the seas, noteworthy land deposits no longer form, and slight elevation of the ocean sursurface will cause it to widely transgress the base-leveled land.

Turning to the marine deposition of mechanical sediments, they should be observed to immediately increase in volume following continental uplift, several chief types being noted according to the nature of the land and the movement of uplift. If from a near-by mountain range, the sediments will be coarse in nature and formed through rock disintegration more largely than through decomposition. If from an older coastal plain, the marine deposits will comprise siliceous residues from a previous period of erosion. If from a decomposed regolith of a former near-by low-lying land, the sediments will be

[1] The Ulterior Basis of Time Divisions and the Classification of Geologic History, *Journal of Geology*, Vol. VI (1898), pp. 449–62.

[2] *Ibid.*, p. 455.

marked by an abundance of leached argillaceous and ferruginous silts discharged at numerous points along the coast. If from a distant mountain system, the material will be similarly fine-grained, but will show less decomposition and leaching, and be discharged in great quantity by great rivers at a few widely distant points. Thus there are a variety of types of marine sedimentation, the material becoming more uniform in character and more widely spread over the growing circum-continental shelves as the erosion passes into the stages of maturity. Finally, with old age the amount of mechanical detritus greatly lessens, the conditions for limestone formation approach near to the shores, but greensands and the limy shales are still indicative of the presence of land-waste long after all *subaerial* detrital deposits have ceased to form.

Even in old age, however, it is still possible that slight regional uplifts and warpings may result in a temporary renewal of rapid erosion, since under such circumstances the regolith will have formed a deep and voluminous mantle to the continent, readily removed and swept to sea upon the least rejuvenation of the rivers. If the movement is accompanied by an adjacent down-warping in a continental interior, the deeply decayed rock mantle may be swept into it and be built up by river aggradation as a continental deposit, which further warping may carry beneath the sea.

GENERAL APPLICATIONS TO GEOLOGICAL HISTORY

Having sketched these outlines of the relations of continental and marine sedimentation to the broad earth-movements which have separated and individualized the geological ages, it will be in order to apply them, by way of illustration, to certain typical periods. It will be seen that they suggest, though they do not prove, rather different interpretations for certain formations from those which have been ordinarily held.

Pre-Cambrian æon of continental extension.—It is a matter of familiar knowledge that nearly everywhere the marine deposits of the Cambrian lie upon a far older and unconformable basement. Occasionally the Cambrian appears to have a downward unfossiliferous extension, as in the southern Appalachians, or sometimes rests unconformably upon older, usually barren sediments, but little

or no more metamorphosed than itself, as in Montana and in Arizona. More frequently, however, over all the continents it rests directly upon steeply dipping gneisses and schists. These structures, characteristic of the zone of rock-flowage, indicate widespread and profound erosion previous to the Cambrian transgression, and therefore a period of wide and long-enduring continental extension.

The usual concept of the development of the North American continent embodied in the textbooks of the past begins with the widespread submergence of the late Cambrian and early Ordovician. From that stage Dana has long since shown how the continent through the Paleozoic gradually, and with many regressions, gained in dry land.

Walcott considers, however, that the prevailing view of the geographic distribution and extent of the continental area at the beginning of Paleozoic time is too restricted, and that the continent was larger at the beginning of the Cambrian period than during any subsequent epoch of Paleozoic time.[1] At this date (1891) Walcott had not yet separated the underlying belt formation of Montana from the Cambrian, and consequently considers this portion of the Northwest to have been beneath the sea during Lower Cambrian time. With the discovery of an uncomformity separating the Belt from the Middle Cambrian,[2] this statement in regard to the extent of the early Cambrian land is further justified, and will probably be considered by those familiar with the subject as very conservative.

LeConte also emphasizes the significance of the Pre-Cambrian record of erosion, the subject being briefly stated in his *Elements of Geology*.

A truer appreciation of the facts of the world-wide Pre-Cambrian unconformity may finally lead to the erection of this Pre-Cambrian period into an æon of continental extension as widespread and as long-enduring as that of the Mesozoic and Cenozoic.

Yet it is only the end of this period, as marked by the Lower Cambrian unconformity, which is known with any accuracy. On going backward in time, evidences of repeated orogenic movements

[1] "The North American Continent during Cambrian Time," *Twelfth Annual Report* (1891), U. S. Geological Survey, Part I, p. 562.

[2] C. D. Walcott, "Pre-Cambrian Fossiliferous Formations," *Bulletin of the Geological Society of America*, Vol. X (1898), p. 210.

are encountered widely separated in time, deforming older basins of sediments, and resulting in erosions and unconformities. It is not to be implied, therefore, that such formations as the Belt of Montana and the Grand Canyon terranes, because they lie immediately below the Middle Cambrian, were necessarily deposited in an *immediately* Pre-Cambrian period.

From the thickness of their detrital accumulations situated in the interior of the continent, they probably belong to interior basins of subsidence within rather wide land masses. That these basins were, at least during a part of the time, connected with the open sea is shown by limestone formations, thousands of feet in thickness, which they contain.

In the Lewis and Livingston Ranges Willis has measured a thickness of the Algonkian of about 10,000 feet, without either the upper or lower limits being visible. Of this from 4,500 to 5,300 feet are argillites and quartzites, while 5,400 feet are limestones, divided into two great formations.[1]

Near Helena, in west-central Montana, Walcott has estimated the total thickness of the Belt terrane at 12,000 feet, of which 7,600 feet consist of argillites and quartzites, the remainder, as before, being divided into two great limestone formations.[2] This region is possibly not far from the limits of the original basin during much of the time of deposition, since the Belt formations disappear from between the older gneisses and the younger Cambrian some 60 miles to the south.

In the Pre-Cambrian Grand Canyon series, exposed in northwest Arizona, Walcott gives the Unkar and Chuar terranes a combined thickness of 11,950 feet, of which about 400 to 500 feet are limestones, and about 1,000 feet lavas. The remainder are sandstones and argillites.[3]

In view of these great thicknesses of sandstones and argillites accumulated in interior basins of Montana and Arizona at a time of at least considerable continental extension, the hypothesis of a subaërial origin by river aggradation may well be held in mind as a possibility for certain formations, as well as the more common

[1] *Bulletin of the Geological Society of America*, Vol. XIII (1902), pp. 316, 317.

[2] *Ibid.*, Vol. X (1898), p. 204.

[3] *Fourteenth Annual Report*, U. S. Geological Survey, Part II, pp. 508–12.

hypothesis of the accumulation of such materials at the bottoms, or within the margins, of shallow seas.

Again, in the Lower Cambrian, according to Walcott, the eastern side of the narrow Appalachian trough appears to have been a bold and precipitous mountainous area. In the trough itself beneath the Olenellus sandstone occurs a great series of variegated shales.[1] These are of course no proof of land accumulation, but the geographic relations of land and water were such as to suggest the possibility that delta deposits may have been built out into a trough which later, by a slackening of erosion or a greater subsidence, allowed the region to pass from largely subaërial to marine conditions, the marine transgression being marked by the deposit of the Olenellus quartzites.

In conclusion it is suggested that the Pre-Cambrian and Lower Cambrian ages of wide continental extension offered conditions favorable for the accumulation of the several types of subaërial deposits, and that in the interpretation of the mechanical sediments of those times this possibility should be always held in mind. The presumed absence of a fossilizable land fauna and flora in the life of those periods would remove the possibility of proving a continental origin through such secure means.

Paleozoic epicontinental basins.—During the Eopaleozoic the continents became largely submerged, but in the Neopaleozoic partial emergence was the rule, varying from fairly extensive land conditions at times (in late Silurian and Lower Devonian), as has been shown by Ulrich and Schuchert,[2] to submergence possibly nearly as complete as that of the Ordovician. At times mountain-making forces and regional uplift operated on an extensive scale, as is witnessed, for example, by the enormous mass of Upper Devonian sediments along the northeastern portion of the Appalachian trough from which Willis computes that the uplift supplying these sediments corresponded in volume to a mountain range similar to the Sierra Nevada,[3] and the sediments deposited in the Old Red Sandstone

[1] "The North American Continent during Cambrian Time," *Twelfth Annual Report*, U. S. Geological Survey, Part I (1891), pp. 536, 551.

[2] "Paleozoic Seas and Barriers in Eastern North America." *N. Y. State Mus., Bull. No. 52*, pp. 633-663, 1902.

[3] *Paleozoic Appalachia*, Maryland Geological Survey, Vol. IV (1902), p. 62.

basins of the British Isles, Norway, and the Arctic islands to the north.

This mountain-building, taken into consideration with the restricted nature of the interior sea of eastern North America between the Cincinnati axis and the eastern border, forms geographic conditions which should favor the development of extensive deltas filling up shallow seas and giving rise to the formation of subaërial deposits. Turning to the strata themselves to find an answer to this suggestion, one notes the sparingly fossiliferous character of the Catskill group of the Upper Devonian and the fact that the few fossils found are those of fishes, Eurypterids (Stylonurus), and some fresh-water lamellibranches (Amnigenia), suggesting that, occasionally at least, subaërial deltas may have covered considerable regions, and should be looked for by a critical study of textures and structures. Many geologists would grant this possibility, though it has found but little recognition in geological literature.

That differences of view among able living geologists may be held upon the subject of the Paleozoic formations is indicated by the fact that Willis, as a result of his prolonged and detailed studies of the Appalachians, interprets the Tuscarora (Medina) sandstones of Maryland as submarine coastal plain deposits,[1] while more recently Grabau, in a preliminary paper, advances the hypothesis that the Siluric conglomerates and sandstones are part of a huge subaërial fan, whose apex was in southeastern Pennsylvania.[2]

This is not mentioned with the intention of urging the continental point of view, since the cleanly sorted character of much of the formation would seem to indicate to the present writer that prolonged sorting by waves, rather than the limited sorting and variable character of river work, had been concerned. It might well be, however, that an alternation of conditions has occurred, marine deposition dominating in one district, river work in another.

Of the Paleozoic formations it is in the coal-measures, however, that the relations between continental and marine deposits are most distinctly shown and most fully appreciated; largely because the climatic conditions were such as to lead to the formation of swamp

[1] *Op. cit.* (1902), pp. 55, 56.

[2] "Physical Characters and History of Some New York Formations," *Science*, New Series, Vol. XXII (1905), p. 533.

jungles whenever delta surfaces were exposed to the air without either uplift sufficient to produce erosion or subsidence sufficient to result in burial. With occasional exceptions, which may be due to river driftage, it is conceded that the coal was formed *in situ*, and thus each coal-bed becomes a determined land surface, although once in a swamp condition.

The analogy of the carboniferous swamps with those existing at present upon delta surfaces or buried beneath the later river deposits has been perceived and pointed out since the time of Lyell. This analogy, together with the usual absence of marine fossils and the occasional presence of land or fresh-water forms in the associated strata, has led to the well-founded belief in the chiefly fresh-water or brackish-water origin of the coal-measure shales and sandstones of Nova Scotia, the Pennsylvania anthracite basins, and other regions. But over the western portion of Pennsylvania and much of the continental interior, beds of limestone with marine fossils occur at intervals through the coal-measures, indicating in those regions periodic invasions of the sea.

From these facts it is inferred that periodic subsidences took place, allowing transgressions of the widespreading epicontinental sea across the submerged delta surfaces. But the absence of the limestones nearer the shore and in basins like that of Nova Scotia, where the great thickness of shales, sandstones, and conglomerates testifies to rapid erosion and sedimentation, indicates that subsidences did not allow the sea to reach this far inland, but that it was kept out by the rapidity of river aggradation, which, as the basin subsided, distributed mud, sand, and gravel *pari passu* over the old forest swamp. Thus, the same conclusion is derived inductively as that previously arrived at by deduction concerning the phenomena of a subsiding delta region, where it was concluded that the marine and continental portions should be broadly interfingered, the sea cutting in from one side, the rivers building out from the other, and the littoral being a relatively unimportant transition zone resulting from the contest between the two.

Statements might be quoted from able writers in which it is assumed that the subsidences were of an oscillatory nature, and that the reclamation of the land surface from the sea was due largely to

uplifts which would cause the sea bottom to just emerge above the sea-level when coal-swamps would form, while subsidences would carry it downward, maintaining depths of 100 feet or more during which sediments were being deposited.

Upward oscillations are, of course, not to be excluded, but in regard to the major cause of land-surface reclamation the following may be quoted from Geikie:

> It has been assumed that, besides depression, movements in an upward direction were needful to bring the submerged surface once more up within the limits of plant growth. But this would involve a prolonged and almost inconceivable see-saw oscillation; and the assumption is really unnecessary if we suppose that the downward movement, though prolonged, was not continuous, but was marked by pauses, long enough for the silting-up of lagoons and the spread of coal jungles.[1]

LeConte emphasizes the same conclusion as to the cause of the alternation of strata; it being due not to crustal oscillation, but to the operation of two opposing forces, one depressing (subsidence), the other upbuilding (river deposit), with varying success.[2]

Dana also states that, when

> under verdure, the surface must have lain for a long period almost without motion; for only a very small change of level would have let in salt water to extinguish the life of the forests and jungles, or have so raised the land as to dry up its lakes and marshes. Hence the grand feature of the period was its prolonged eras of quiet, with the land a little above the sea-limit.[3]

It is inconceivable that uplifts should have terminated and the land rested quietly almost indefinitely when it was brought exactly to the sea-surface, and it has been shown in the earlier part of this article that the sea and land always tend to be differentiated.

It is seen then that, supposing a small subsidence of, for example, 100 feet to take place, the river building would on the landward side keep pace with it. The coal-jungles would first be quietly flooded with fresh-water lagoons, as over portions of the Ganges delta. In these clays would be laid down, quietly burying and protecting the extinguished forest, and preserving within itself numerous fossils of ferns and leaves. Following this, the shifting river distributaries would deposit sand, or possibly even gravel, the whole

[1] *Text-Book of Geology*, 4th ed. (1903), p. 1018.

[2] *Elements of Geology*, revised ed., p. 390.

[3] *Manual of Geology* (1895), p. 708.

covered continually with sufficient vegetation to leach out by its decay the iron from the deposited sediments, but not standing in water, and therefore finally destroyed by oxidation.

On the seaward side the subsidence brings about a transgression of the sea with considerable erosion of the forerunning transitional littoral zone, or even of the underlying fluviatile and swamp formations, such as is sometimes observed to have occurred in the coal-measures of Illinois, Kentucky, and Missouri. In order to observe the process of land-reclamation by the river deltas from the sea, suppose, to continue the example, that the subsidence has been sufficiently rapid for the sea to gain 10,000 square miles from the land with an average depth of 50 feet, at which time the subsidence ceases.

The Ganges annually carries across its delta to the sea sufficient sediment to cover one square mile 221 feet deep; the Mississippi annually discharges into the Gulf of Mexico sufficient to cover one square mile 268 feet deep. Applying these figures to the hypothetical case, and assuming that one-half of the discharged sediment goes to make the fore-set beds by which the delta is built outward, it is seen that the Ganges would completely reclaim this area in 4,524 years, the Mississippi in 3,730 years. These, however, are two of the greatest rivers. But even if the carboniferous rivers discharging across the region of the Appalachian coal-fields delivered but a tenth part of the detritus borne to the sea by the Ganges and the Mississippi, it is seen that the transgressive effect of the supposed subsidence would be completely nullified in periods of 45,240 and 37,300 years. During this period of quiet and of land extension, conditions for the formation of coal would exist over much of the delta surface not actually traversed by the rivers, the swamps by the deposit of organic débris keeping pace to some extent with the distributaries raising their beds as the delta advances, and thus tending to prevent the wandering of the rivers across them.

In the present connection it is desired to emphasize not only the upbuilding but the outbuilding capacity of rivers, by which, if their sources are in highlands, their deltas may rapidly push into and fill up shallow epicontinental seas. Under such circumstances it is largely a question of the rate of river deposition and the volume of the sea to be filled.

In conclusion, then, it may be said that during the Paleozoic the eastern margin of the United States witnessed repeated uplifts and occasional mountain-making movements, which poured down great quantities of sediments into a shallow and at times restricted interior sea. These conditions should lead during times of rapid erosion to extensive subaërial deltas; sometimes temporary fresh-water marshes or periodically inundated desert flood-plains; sometimes verdure-covered swamps and plains: deltas showing great thicknesses of subaërial beds advancing to a considerable distance into the sea, alternating with periods of relatively more rapid subsidence or slackened erosion when the sea would transgress across the subsiding delta. At present the coal-beds, and the occasional presence of shells of fresh-water facies in the associated dark shales, are considered the only decisive evidence of such conditions, but the absence of coal-beds does not prove the contrary side of the question.

Mesozoic and cenozoic continental deposits.—The possibility of the occurrence of Mesozoic continental deposits has been widely recognized in both the New and Old World, especially for the closing stages of the Paleozoic and the opening of the Mesozoic, when the continents appear to have been broadly uplifted concomitantly with orogenic movements, and conditions of coldness and aridity occurred in many parts of the world, coldness and humidity in others. The conditions seem to have been of a somewhat similar nature to those recurring at the end of the Tertiary and enduring in a measure to the present time. It does not seem necessary, therefore, in the present connection to enter into a detailed discussion of the possibly or probably subaërial Mesozoic deposits of Europe, Asia, and America. Neither is it necessary under the present heading to discuss the deposits of the Tertiary and Quaternary still enduring at the surface, since it is the accumulated knowledge of these which has been used as the key and the test of this discussion, and it is by a further study of them that added light will be shed upon the past.

CORRECTION.—Through a printer's error the titles of Figs. 3 and 4 in Part I, pp. 347 and 349, were transposed.

Reviews and Book Notices

An Introduction to Astronomy. By Forest Ray Moulton. London-New York: The Macmillan Co., 1906. Pp. 557.

As geology is the domestic chapter of astronomy, the broad-minded geologist cannot be indifferent to the appearance of a synoptical treatise which brings within easy reach the essential advances in this old but ever new and fascinating science. Dr. Moulton's book is eminently opportune and welcome, since it covers in clear and firm terms those phases of astronomy which are just now most serviceable to the student of the genesis of the earth. In the first fourteen chapters the book sets forth the methods by which the science is developed, the important features of the solar system, and the mechanical principles involved in celestial dynamics. The selection of the matter is notable in that the most fundamental and essential facts are chosen, rather than those that are of most spectacular and superficial attractiveness. Perhaps in no other book of its kind is there so large a proportion of the things that it is essential for one to know, if one is to follow the progress of astronomical geology, as in this treatise, modestly styled an introduction to astronomy. And as these come from the hand of a specialist in celestial mechanics, they may be accepted with unusual confidence. A notable feature of the treatment is the close tying of facts to principles, by virtue of which the facts teach the principles, and the principles give the facts coherence and meaning, and help one to hold them.

On the firm grounding of facts set forth in the first fourteen chapters, the evolution of the solar system is discussed with a fulness and precision found in no other astronomical work of its grade. The views of Thomas Wright and Kant are briefly noticed, while those of Laplace, Lockyer and George Darwin are more fully treated. The facts that support the Laplacian view and its modifications are cited and set over against the facts inconsistent with it, especially those that have been developed by recent studies and discoveries. The planetesimal or spiral-nebular hypothesis is as fully set forth as the limits of such a work permit, and, naturally, as coming from one who has taken an essential part in its development, in an appreciative and sympathetic way. Dr. Moulton's treatment is in many respects different from that of Chamberlin, though completely in harmony with it, and to those to whom the mathematical form of treatment is helpful it will doubtless be found more acceptable. It may, however, be easily fol-

lowed by those who are not deeply versed in mathematics, as only the simpler formulæ are introduced. In the summary at the close of this chapter on evolution, after a word of warning that this theory should not be accepted as final, since many phenomena having a critical bearing upon it are yet to be developed, Dr. Moulton says:

> The development of a spiral nebula by the near approach of two suns seems to be a necessary consequence, though this point needs further elaboration. The development of some such a system as ours from a small spiral nebula of the type considered seems to be inevitable. So far as the details have been worked out, nothing directly contradictory to the theory, or even seriously questioning it, has been found, while it explains admirably all the main features of the system. It can be safely said that, at present, this hypothesis satisfies all the requirements of a successful theory much better than any previous one.

The final chapter is devoted to stars and nebulæ in which, as before, the selection of the important things is notable. The work is to be heartily commended to the geologist who wishes a brief and trustworthy summary of the recent developments in astronomical science. T. C. C.

A Preliminary Report on a Part of the Clays of Virginia. By HEINRICH RIES, PH.D. (Geological Survey of Virginia, Bulletin No. II, 1906.) Pp. 184, 15 plates, 10 figures.

The investigation of the clays of Virginia has been well begun, and when completed it is proposed to publish a volume on the clay industries of the state. So far attention has been confined to the coastal plain belt. The expressed purpose of this work is to determine (1) the extent, qualities, and applicability of the clays; and (2) whether the clays now being utilized could be used for making other and better products than are now being made from them. To this end many samples were collected and carefully investigated both chemically and physically. The results of these investigations together with instructive discussion of the origin, properties, and mode of occurrence of clay, methods of mining and manufacture, etc., are embodied in this report.

The first chapter, forming Part I of this report, treats of the "Geology of the Virginia Coastal Plain" and was contributed by William Bullock Clark and Benjamin LeRoy Miller. The interpretation of the Sunderland and other Pleistocene formations is given in unqualified terms as though unquestioned science, with no intimation to the reader that the interpretation is questioned and other interpretations advanced. The public are entitled to know the true state of the case. E. W. S.

Geology of the Central Copper River Region, Alaska. By WALTER C. MENDENHALL. (U. S. Geological Survey, Professional Paper No. 41, 1905.) Pp. 133, 20 plates and maps, 11 figures.

The area described lies in the central and northern parts of the copper River Basin—one of the most interesting regions in southern Alaska. It came into prominence in 1898, at the time of the great stampede to the Eldorado of the north. Some of those who overcame the difficulties of getting into the Copper River country were rewarded by finds of considerable copper and gold deposits.

Three great mountain ranges cross the area—the Chugatch, the Wrangell, and the Alaskan. Mount Wrangell itself is an active volcano which constantly gives forth great volumes of smoke and vapors. Mount Sanford, one of a number of extinct volcanoes, is 16,200 feet high—the highest peak in the region. The southern side of the Alaskan range is a great fault scarp, and Mr. Mendenhall believes the whole Copper River valley to be due to a sunken fault block. He also thinks it probable that this sinking was the result of the outpouring of the Wrangell lavas.

Another interesting scientific contribution is the description of 6,000–7,000 feet of Permian strata in the upper Copper River valley. The fauna is much more closely related to that of the great limestones of India than to the fauna of the Mississippi valley Permian. This is probably one of the best developments of marine Permian in the world. E. W. S.

Geology of the Boulder District, Colorado. By N. M. FENNEMAN. (U. S. Geological Survey, Bulletin No. 265, 1905.) Pp. 101, 5 plates, 11 figures.

The principal topic of this report is the gas and oil of the district, but it treats also of the physiography, stratigraphy, structure, geologic history, and its other economic resources. These are: water, building-stone, grindstone, lime, clays, and coal. The area lies at the foot of the Front Range, and has its appropriate topography of plains on the east, and mesas and foothills on the west. The rocks are nearly horizontal sedimentaries on the east, and the upturned edges of the same against the Archean mass on the west. The oil-producing formation is the Pierre. The producing wells are in a narrow north-south belt, which was found to be the area of a monoclinal fold. Shooting of wells was found to have an injurious effect in many cases, the flow of such wells decreasing after the shooting. Thirty-nine thousand barrels of oil were produced in 1903. One gas well furnishes 3,000,000 feet per month. E. W. S.

Recent Publications

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